Modern and Recent Seafloor Environments (Sedimentary, Foraminiferal and Ostracode) of the Pitt Water Estuary, South-east Tasmania

VOLUME 2

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of the degree of Doctor of Philosophy

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DECLARATION

This thesis contains no material which has been accepted for a degree or diploma by the university or any other institution, and to the best of the author's knowledge and belief no material previously published or written by another person except where due reference is made in the text.

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CHAPTER 10. RECENT SEAFLOOR ENVIRONMENTS - AIMS AND METHODS

10.1. Aims and methodology

The second major aim of this project is to describe the historical change in the seafloor environments of the Pitt Water Estuary, and to determine the cause of these changes. This will be achieved by the analysis of short cores, and by the comparison of spatial surveys of the estuary from different time periods (1968, 1991, and 2001). Each short core provides information from a single location for a range of years; whereas, each spatial survey provides information from a range of locations for a single year.

The knowledge gained in chapters 6 to 8 on the relationship between certain environmental factors and the current distribution of sediments and benthic fauna in the estuary, can be used to interpret historical changes in the distribution of sediments and benthic fauna as changes in the distribution (or value) of specific environmental factors. Consequently, from the understanding gained in chapter 9 on the effects of current human activities upon the modern estuarine environment, the timing of historic changes to these environmental factors can be related (using the known history of human activity in estuary and catchment) to specific events or processes.

10.1. 1. Core data

The object of the short core analysis is to identify, at specific locations, historic changes in seafloor environments, and to match these changes to human activities, or natural processes, which have occurred in the past. Seafloor environments can be identified within each core by identifying ‘biozones’ at different core sections which provide an indication of the environmental conditions during different time periods. These ‘biozones’ were identified using combined cluster analysis of the foraminiferal and ostracod species composition data of both core sub-samples and the modern samples used for cluster analysis in chapters 7 and 8. Consequently, core sub-samples have been grouped with many of the previously described sample associations identified in the modern environment, thus, allowing palaeoenvironments to be described. In addition to the identification of ‘biozones’, trends or sudden changes in species composition between, and within, different core intervals, as well over the entire length of each core, were used to further describe the change in seafloor environments.

10.1.2. Spatial surveys

Comparing the modern distribution of sediments, foraminifera and ostracods to that described in previous spatial surveys, allows analysis of how the seafloor environments of the estuary have changed in recent years. As these previous spatial surveys were made in 1968 (of the entire estuary) and 1991 (of Orielton Lagoon), comparison to the modern environment indicates how the entire estuary changed from 1968 to 2001, and how Orielton Lagoon changed from 1991 to 2001. Any changes in sediments and benthic fauna can be related to a change in the environmental factors described in previous chapters, allowing a link to historic activities which occurred during these time periods.

In order to make comparisons with the study by Harris in 1968, some sediment and benthic faunal analysis techniques have been replicated, such that data of similar form could be compared between both studies. It is not known which taxonomy Harris (1968) followed, so possible modern equivalents of some species have been suggested.

10.2. Methods used in short core analysis

Two categories of methods were used for the purpose of short core analysis. The first category involved the fieldwork, which consisted of the collection of the short cores; whereas, the second category involved laboratory analysis of the cores.

10.2.1. Methods used in fieldwork

Four short, Late Holocene cores were obtained from the upper estuary in 2001-2002 by Iona Mitchell (Tasmanian Aquaculture and Fisheries Institute) as part of a AINSE funded study assessing the historical linear changes in sediments and sedimentation rates down the estuary, as well as changes in molluscan composition and saltmarsh sediments (Mitchell et al., 2005) (Figure 10.1).

The Midway Bay core was collected using a purpose-built diver-operated coring device constructed by Iona Mitchell (TAFI), consisting of a perspex tube (9 cm in diameter, 80 cm in length). The device was pushed into the sediment by hand and removed once a waterproof cap was placed over the top of the core so to provide a vacuum seal. Sediment was extruded from the core and sectioned at 1.2 cm intervals as it was removed from the core device using a Perspex ring, with each 1.2 cm section divided into half. One set of sub-sample halves was used in the study by Mitchell et al. (2005); whereas, the other set were used in a diatom study of the core by Lane (2004). The set of sub-sample halves from the latter study was subsequently passed on to the current study. At the time of collection

of the Midway Bay core, salinity, temperature and water depth was measured with a CTD meter, and water clarity was measured with a Secchi disc.

The Samphire Island, Duckhole Rivulet and Stinking Point cores were collected at approximately 0.5 m water depth during low tide, by pushing a 9 cm diameter PVC tube into the substrate, and capping the tube to create a vacuum seal. In the laboratory, these cores were halved lengthwise, with one set of halves used in the study of Mitchell et al. (2005), and other set passed on to the current study.

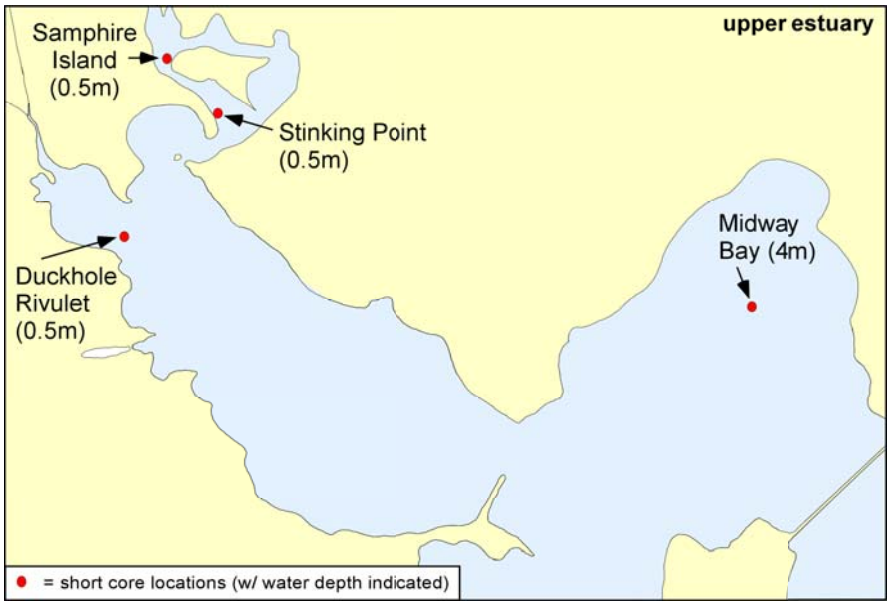

Figure 10.1. Location of short core sample sites (water depth of each site indicated).

10.2.2. Methods used in laboratory

Initially, each core was logged lithologically, being separated into different units on the basis of shell and mud content. Shelly sediments were divided visually into three categories: highly shelly (where shell content >> sand content), moderately shelly (shell content = sand content), and slightly shelly (shell content << sand content).

Apart from the Midway Bay core (which was sub-sampled at 1.2 cm intervals), each core was sub-sampled at approximately 5 to 10 cm intervals, although more closely spaced sub-samples were taken from positions of lithological and faunal changes. Each sub-sample was obtained by pushing an open-ended, plastic film canister into the half-cores, with each sub-sample having a downcore length of 2.5 cm, and a horizontal length of 6 cm.

10.2.2.1. Sediments

Before sub-samples of the Midway Bay core were passed on to the current study, Lane (2004) performed a particle-size analysis by using 63 um, 125 um, and 2000 um sieves.

Lane (2004) also had these sub-samples analysed for sediment total organic carbon (TOC) by the Central Science Laboratory at the University of Tasmania, using a Thermo Finnigan Flash Elemental Analyser (1112 Series).

In the current study, sub-samples of the other three short cores were initially wet sieved at 63 um, with the mud fraction being retained, dried and weighed. The sand fraction was also dried, and sieved with 125 μm, 250 μm, 500 μm, 1000 μm, and 2000 μm sieves. All sediment fraction weights were then converted to proportions of the total sediment weight. Observations were also made of the sand fraction under binocular microscope, with lithic sand content, sand sorting and roundness, and plant material content being estimated.

The Samphire Island, Duckhole, Stinking Point, and Midway Bay cores were dated as part of the study by Mitchell et al. (2005), using ^{210}Pb isotopes dating of sediment sub-samples. The ^{210}Pb dating method uses excess ^{210}Pb concentration depth profiles to calculate annual sedimentation rates, and thus, age profiles of cores (Durham and Joshi, 1984). Sedimentation rates were calculated by Iona Mitchell (TAFI) using the Brugam model variation of the constant initial concentration (CIC) model (Appleby & Oldfield, 1978; Heijnis, 2001), as well as a simple sediment model factoring mixing depth (McMinn et al., 2001). ^{210}Pb isotope dating was undertaken by the Australian Nuclear Science and Technology Organisation (ANSTO) in Sydney.

10.2.2.2. Microfossils

The sand fraction (> 63 μm) was analysed under binocular microscope, with foraminifera and ostracods picked out manually, identified and counted. Species diversity (Fisher α Index) and abundance were calculated for all sub-samples, with agglutinated foraminifera content also calculated. Separate foraminiferal and ostracod Q-mode cluster analyses were performed, using a dataset of all surficial samples and core sub-samples with at least 5% abundance in at least one sample. Most core sub-samples were placed into previously defined sample associations; however, new sample associations were also created.

The Midway Point core was the focus of a diatom palaeoenvironmental reconstruction by Lane (2004). In that study, transfer functions for $NO_{2\text{-}3}$ and SiO_2, created from diatom analysis of 51 sites collected from the near-shore, subtidal marine zone of south-east Tasmania, were applied to the diatom species training set from the Pitt Water core using C^2 software (Juggins 2003). This produced nutrient and silicate concentrations for numerous depths within the core.

CHAPTER 11. RECENT SEAFLOOR ENVIRONMENTS - SHORT CORE ANALYSIS

11.1 Introduction

In this chapter, the recent development of the estuarine environment is investigated by analysis of four short cores collected in 2001-2002. By analysing the change in sediments, foraminifera and ostracods over time within each of these cores, changes in the estuarine environment can be described, and, consequently, these changes can be related to historic activities within the estuary or catchment area.

The chapter is divided into six sections, including the current introduction. The next four sections each describe a short core. The final section provides a summary and conclusions of all the cores, focusing on palaeoenvironments and associated historical activities.

11.2. The Midway Bay core

11.2.1. Introduction

This core was obtained from approximately 4.2 m water depth in Midway Bay on November 22, 2001. As reported in Lane (2004), 1.2 cm sections of the core were subjected to particle-size and total organic carbon analysis, and all diatom species were identified. From the fossil diatom record, transfer functions for NO_{2-3} and SiO_2 were constructed (Lane, 2004).

Sub-samples of the Midway Bay core inherited from Lane (2004) were sieved at 63μm, and the sand fraction was analysed for foraminifera (complete species lists displayed in Appendix F), with ostracods being absent. Lithic sand content, sand sorting and roundness were also estimated under binocular microscope.

11.2.2. Lithostratigraphy

The core is 68.4 cm long and consists of dark grey, sandy mud, typical of surficial sediment in the deeper areas of the upper estuary.

11.2.2.1. Core dating and sedimentation rates

^{210}Pb analysis dated the base of the core to the early 1880's, with two slightly different sedimentation rates calculated for the core: 0.536 cm/year before 1960, and 0.542 cm/year after 1960 (Mitchell et al., 2005). Table 11.1 displays the age data used by Mitchell et al.

(2005) to construct the time-line displayed in Figure 11.1, using the relationship between sedimentation rate and core depth. An error range occurs in years for each sample dated (Table 11.1), and should be considered whenever dates are used in this section. A mixed surface layer occurs in the top 4.3 cm of the core.

Depth (cm)	+/- years	Corrected age	Corrected year
0.7	Mixed surface layer (2001)		
4.3			
9.1	1.7	10	1991
16.3	2.7	24	1977
25.9	4.1	41	1960
36.7	5.8	62	1939
42.7	6	72	1929
48.7	6.8	83	1918
57.1	7.9	99	1902
66.7	9.2	117	1884

Table 11.1. ^{210}Pb chronology of the Midway Bay core (from Mitchell et al., 2005).

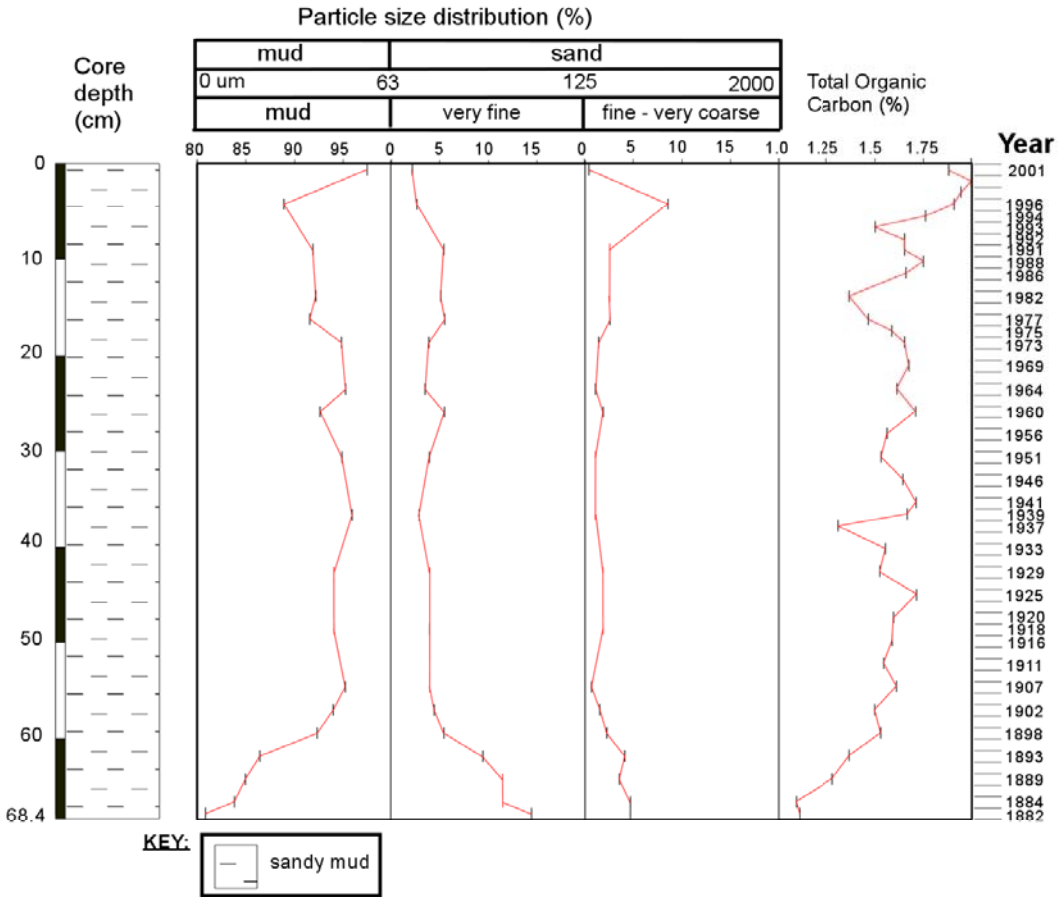

Figure 11.1. Midway Bay core - particle-size distribution data, and total organic carbon content (from Lane, 2004).

11.2.2.2. Particle-size distribution

The sandy muds of the core have a high mud content (as is typical of the modern sandy muds of Midway Bay), ranging from 81 to 97.5%, and averaging 91.7%. For much of the 20th century (from 1907 to 1996), mud content remained relatively stable at 92 – 96%; however, an overall increase occurs upcore as a result of two main periods of increase between 1884 and 1898, and between 1993 and 2001. Between 1884 and 1907, mud content increased from 81 to 95%, with the majority of this change (11.5%) occurring between 1884 and 1898 (Figure 11.1). Between 1996 and 2001, mud content rose from 89% to 98%.

Generally, the 63 – 125 μm sand fraction was greater than the 125 – 2000 μm fraction in all sub-samples indicating that sand was, on average, of very fine grade. Variations in the proportion of sand within each sub-sample are opposite to changes in mud content. Both sand fractions were more abundant between 1884 and 1898 (when mud content was least) with the 63 – 125 μm fraction significantly outweighing the > 125 μm fraction; however, in 1996, the coarser sand fraction was significantly more abundant than the 63 – 125 μm fraction.

11.2.2.3. Sand characteristics

Lithic sand content doesn't vary, representing approximately 20 – 25% of the sand fraction, typical of the modern surficial sediments in Midway Bay. Sand sorting gradually increased upcore, from moderately well sorted at the base to well sorted at the top, corresponding with the decrease in abundance of sand. Sand roundness remained consistent, with grains averaging an angular to sub-angular shape, as is typical of the surficial sands of the area.

11.2.2.4. Total organic carbon

Total organic carbon analysis was performed on the sub-samples by Lane (2004), and the results are displayed in Figure 11.1. Generally, TOC values are quite low, ranging from 1.1 to 2.0%, and averaging only 1.6%. Within the core, TOC values correlate closely with mud content, remaining relatively consistent (averaging 1.5 – 1.6%) for much of the 20th century, yet increasing overall upcore, due to the two main periods of mud increase between 1884 and 1898 (TOC increasing from 1.1 to 1.55%), and between 1993 and 2001 (increasing from 1.5 to 2.0%).

Total Organic Carbon generally refers to the amount of organic matter preserved within sediments, and often shows strong inverse correlations with grain size, adsorbing more to

the surfaces of fine-grained sediment (Logan & Longmore, 2003). Figure 11.2 displays the relationship between TOC and mud content seen throughout the core. In a study of the Huon Estuary, Tasmania, sediment samples with a high correlation between organic carbon and mud content were typical of cases where the organic matter is extensively recycled and adsorbed onto particles before being finally incorporated into the sediments (CSIRO, 2000).

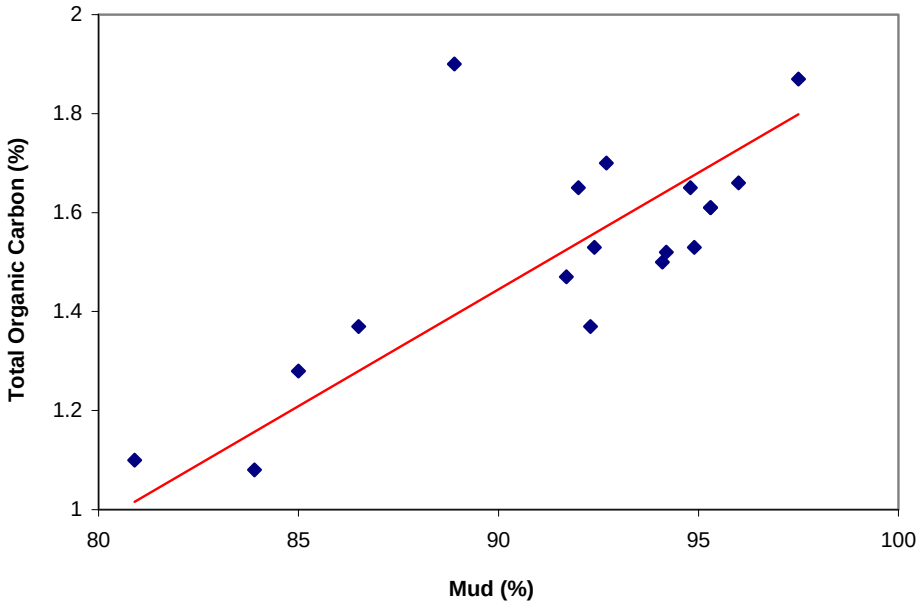

Figure 11.2. Relationship between total organic carbon (%) and mud content (%) in sub-samples of the Midway Bay core (with trendline).

Low concentrations of TOC in the sediments of the core could suggest that organic matter has been consistently low in abundance within Midway Bay since 1884, or that it has not been preserved due to diagenesis or consumption by organisms.

11.2.2.5. Depositional environments

Sandy muds have occupied the deeper waters of Midway Bay (and likely the deeper areas of the upper estuary) since at least 1882. A significant increase in mud content (and a corresponding decrease in sand content) occurred from 1882 to 1907 (mainly until 1898), with either more mud being supplied to the area or more accumulating. The upper 4.3 cm of the core (after 1996) occupies the mixing zone, prone to reworking through bioturbation and resuspension, and was considered by Lane (2004) to contain the lighter resuspended sediment that is last to settle after disturbance. Lane (2004) suggested that little information could be drawn from the sample obtained in this zone.

The sedimentation rate of the area has stayed at approximately half a centimetre a year since 1882, with only a minor increase occurring after 1960. The accumulation of organic carbon in the sediments correlates with the accumulation of mud, having been attracted to fine sediment grains.

11.2.3. Nutrient content

Lane (2004) reconstructed the nutrient history of the upper estuary by applying to the Midway Bay core a training set of diatom information, obtained from other coastal environments in south-east Tasmania, and calculating spring $NO_{2\text{-}3}$ and SiO_2 values for each sub-sample (Figure 11.3).

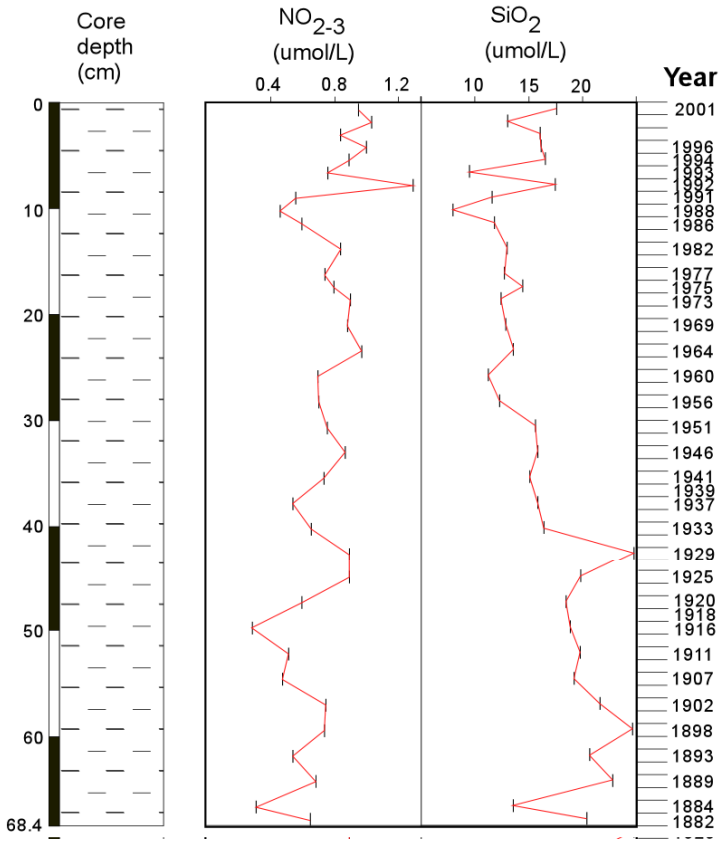

Figure 11.3. Spring $NO_{2\text{-}3}$ and SiO_2 values for the Midway Bay core, calculated by Lane (2004) from diatom data.

11.2.3.1. Nitrate and nitrite

$NO_{2\text{-}3}$ (nitrate and nitrite) are dissolved inorganic forms of nitrogen, with nitrate usually the primary form of nitrogen dissolved in water. Other forms of nitrogen which can be dissolved in water include ammonia and organic nitrogen. Measurement of nitrogen levels in the Coal River by Daley (1999), found that 74% of nitrogen is attached to fine sediment,

whereas, 26% is dissolved in water. Therefore, nitrate and nitrite are only a portion of the total nitrogen in the estuarine system, with a substantial amount being particulate nitrogen in sediments, and further amounts dissolved in water as ammonia and organic nitrogen.

The values of NO_{2-3} calculated by Lane (2004) are an estimate of average nutrient concentrations, each representing approximately two years (Figure 11.3). Crawford & Mitchell (1999) noted considerable variability in the NO_{2-3} concentrations in the modern Pitt Water estuarine system, with NO_{2-3} concentrations varying by more than 40 times in the space of a few months, and average annual concentrations varying by more than 13 times. Lane (2004) therefore considered the range of NO_{2-3} concentrations inferred for the Pitt Water core to approximate real values.

Lane (2004) described NO_{2-3} concentrations as being low to moderate, increasing overall upcore. Peaks occur in the mid- to late 1920's, early to mid-1940's, mid- to late 1960's and early 1990's. The overall increase in NO_{2-3} from 1882 until the present day indicates that the delivery of nutrients in the form of dissolved nitrogen has generally increased since then.

11.2.3.2. Silicate

Dissolved silica (SiO_2) concentrations were calculated by Lane (2004) on the basis of it being a source of nutrients for diatoms. The supply of silicon is particularly significant in coastal phytoplankton dynamics, because of its importance as a structural component of diatoms (Brodie, 1995). It limits the growth of certain types of algae (like diatoms), so it tends to affect what grows, rather than how much grows (European Environment Agency, 1999). Generally, dissolved silicate is not derived significantly from human activities, being sourced by the erosion of minerals from sediments.

Lane (2004) described SiO_2 concentrations as being low to moderate, decreasing overall upcore since the 1930's, with peaks during the late 1890's, mid- to late 1920's and early 1990's (Figure 11.3). As dissolved silicate is derived mainly from the erosion of minerals, fluctuations in its concentration probably reflect variations in the amount of flow entering the upper estuary. Such therefore indicates an overall decrease in flow (probably along the Coal River) since the 1930's.

11.2.4. Fossil foraminiferal distribution and facies

11.2.4.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is low, with Fisher α indices ranging from 0.8 to 2.4, and averaging 1.4, which is typical of the surficial sediments of Midway Bay. With time, species diversity decreased overall, from 1.66 at the core base in 1884, to 0.95 at the top of the core in 2001. Figure 11.4 shows how this decrease has been relatively consistent and gradual, apart from three peaks occurring in the early 1900's, mid-1920's and mid-1960's (the latter greater and more significant).

The overall decrease in species diversity upcore suggests that conditions have become increasingly less favourable to foraminifera within Midway Bay since the late 19th century. A large peak in diversity during the 1960's correlates with a period of lowered foraminiferal abundance. After the early 1960's, species diversity and foraminiferal abundance are inversely correlated, with diversity decreasing upcore as abundance increases. This suggests conditions are favouring the dominance of a smaller number of species.

(ii) Abundance

Foraminiferal abundance varies greatly within the core, ranging from 2.2 to 156 specimens per gram of sediment, and averaging 35. Generally, abundance increases upcore, with this increase being greatest after the early 1970's, peaking during the early 1990's (Figure 11.4). Before the 1970's, abundance was generally very low, apart from two minor peaks in abundance during the mid- to late 1920's, and the early to mid-1940's. After the peak in abundance in the early 1990's, foraminiferal abundance decreased, to be significantly less, yet still relatively high, in 2001. The three peaks in foraminiferal abundance correlate with peaks in $NO_{2\text{-}3}$ values, and, to a lesser extent, with total organic carbon (Figure 11.4).

In the modern environment of the Pitt Water Estuary, foraminiferal abundance has been linked to nutrients, with muddier sediments containing a greater abundance of foraminifera due to the greater nutrient contents of such sediments. Within the core, foraminiferal abundance does not appear to be linked with mud content as in the modern environment. This suggests that nutrient supply to Midway Bay has increased over time, with the muddy sediments obtaining increasingly greater nutrient contents. This is, to some extent, verified by some peaks in abundance of $NO_{2\text{-}3}$ correlating with the three main peaks in abundance,

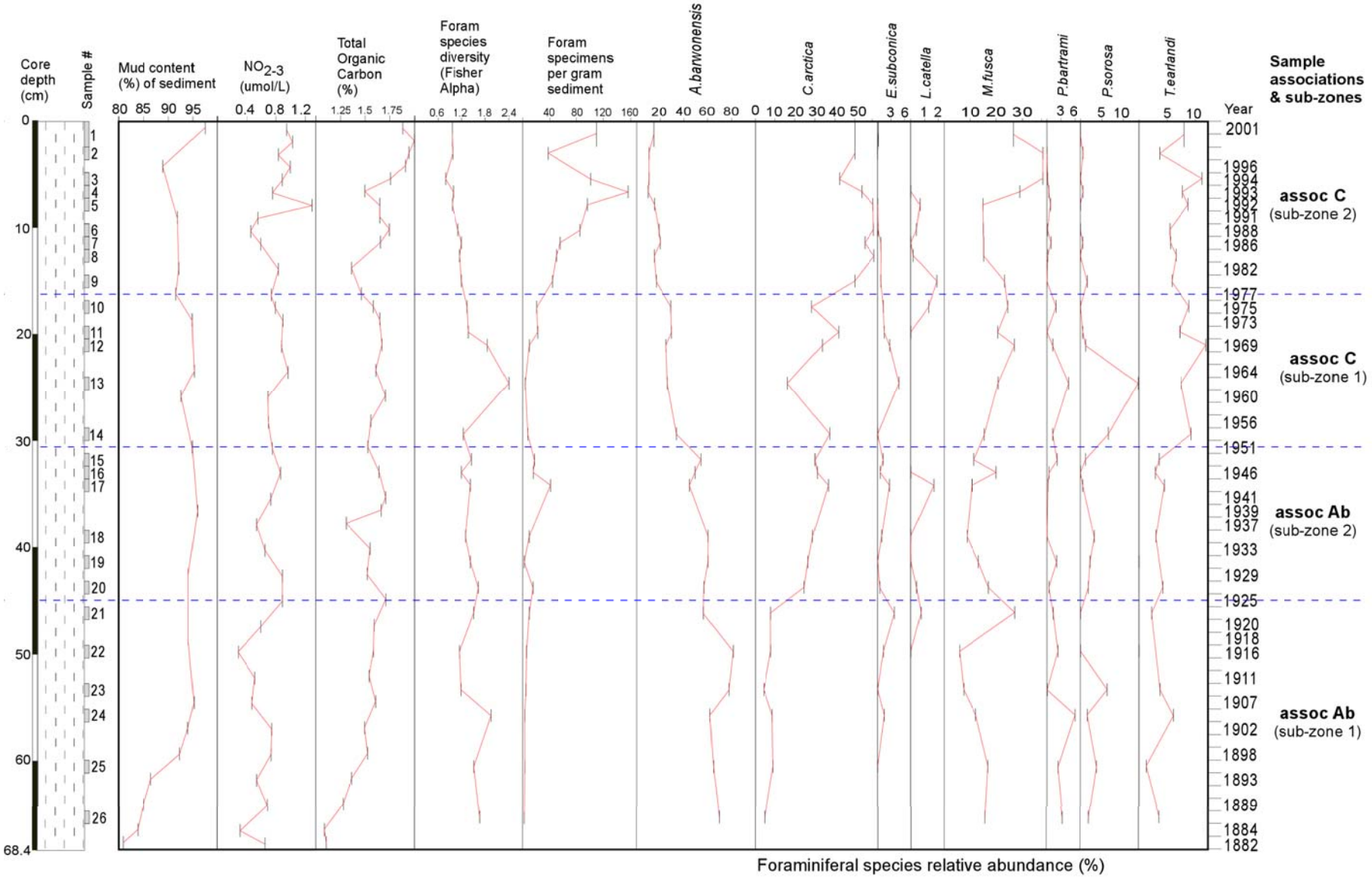

Figure 11.4. Fossil foraminiferal distribution in the Midway Bay core.

particularly during the mid- to late 1920's and early to mid-1940's. However, as the major increase in abundance after the 1970's is not accompanied by a dramatic increase in NO_{2-3} during that time, it is probable that other sources of nutrients (such as phosphorous) are also involved in increasing foraminiferal abundance. Additionally, NO_{2-3} values represent 1-2 year averages of seasonal variations, which could include both high and low nitrate levels.

(iii) Agglutinated content

The foraminiferal fauna of the core consists only of agglutinated species, indicating that bottom water pH in Midway Bay has stayed very low since 1882. This is, as already determined in the modern environment, mainly a consequence of water stagnation. However, the increase upcore in the nutrient content of sediments is likely to have assisted in further lowering pH levels.

11.2.4.2. Sample associations and sub-zones

A combined cluster analysis of all Midway Bay core sub-samples and all modern surficial samples (used for cluster analysis in chapter 7) identified, within the core, foraminiferal sample association Ab between 1882 and the early 1950's, and association C between the early 1950's and 2001 (Figure 11.4). Each of these sample associations could be further divided into two sub-zones. The opposing abundance of the dominant species of the core, *A. barwonensis* and *C. arctica*, provides the major trend in species composition, forming its subdivision into associations and sub-zones. The abundance of *A. barwonensis* decreases steadily upcore, while *C. arctica* increases. However, Figure 11.5 shows that the absolute abundance of *A. barwonensis* (and each of the four main species of the core) actually increases upcore, yet it does so substantially less than that of *C. arctica*, indicating that although most species increase in abundance as nutrients increases, *C. arctica* increases substantially more, such that it becomes the dominant species after the early 1950's. Consequently, peaks in foraminiferal abundance tend to correlate with drops in the abundance of *A. barwonensis*, and peaks in abundance of *C. arctica* (and to a lesser extent, *M. fucsa* and *T. earlandi*).

(i) Association Ab

Association Ab represents the lower half of the core, in sediments dating from 1882 to the early 1950's. The association is dominated by *A. barwonensis* (average abundance of

61%), with subdominant *C. arctica* (17%) and *M. fucsa* (14%), and secondary species *T. earlandi, P. sorosa, L. catella, E. subconica,* and *P. bartrami*. Specimen abundance within the association is quite low with an average of only 10 specimens per gram of sand. Species diversity is also quite low, with the Fisher α Index averaging 1.46.

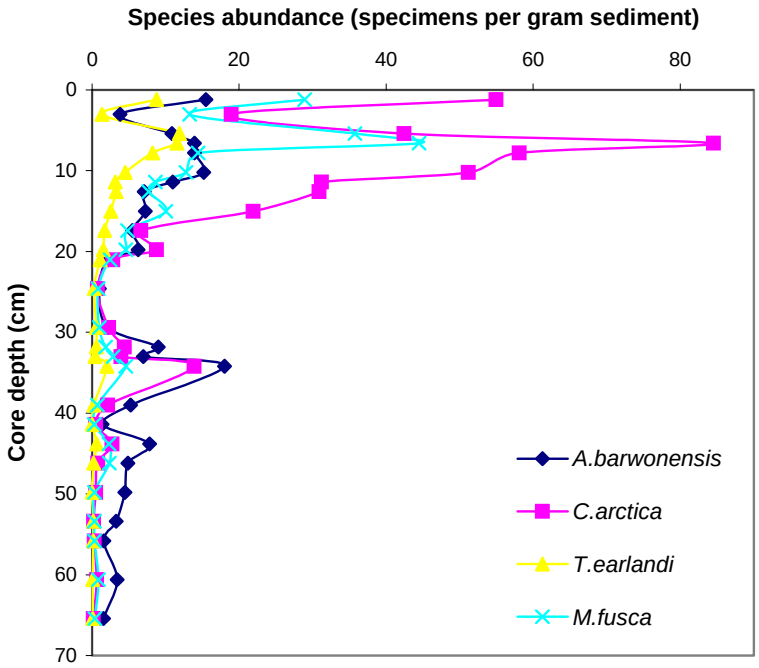

Figure 11.5. Abundance (per gram of sediment) of main species of the Midway Bay core.

The abundance of *A. barwonensis* decreases steadily upcore within the association, with corresponding increases in abundance of *C. arctica*. A substantial jump in the abundance of *C. arctica* occurs during the mid-1920's, and this provided the basis for a subdivision (by cluster analysis) of the association into two further sub-zones. Within the lower sub-zone (sub-zone 1), *A. barwonensis* has an average abundance of 68%, and *C. arctica* of 9%; whereas, in the upper zone (sub-zone 2), *A. barwonensis* has an average abundance of 54%, and *C. arctica* of 26%. With the increase in abundance of *C. arctica* within sub-zone 1, foraminiferal abundance also increased, with average foraminiferal abundance being 5 specimens/gm of sediment in sub-zone 1 and 16 specimens/gm of sediment in sub-zone 2. The boundary between sub-zones correlates with the earliest peak in nutrient content of sediments (as indicated by foraminiferal abundance) and that sub-zone 2 also contains the second nutrient peak of the early to mid-1940's.

The sub-dominant species, *M. fucsa*, and secondary species, *L. catella, T. earlandi*, and *E. subconica* also have minor peaks in abundance which correlate with the nutrient peaks of

the mid-1920's and early to mid-1940's, indicating that increased nutrient supply increases the relative abundance of these species.

(ii) Association C

Association C represents the upper half of the core, in sediments dating from the early 1950's until 2001. The association is dominated by *C. arctica* (average abundance of 62%), with sub-dominant *M. fucsa* (23%) and *A. barwonensis* (21%). Secondary species include *T. earlandi, P. sorosa, L. catella, E. subconica* and *P. bartrami*. Specimen abundance within the association is greater than in the underlying association, averaging 57 specimens per gram of sediment; whereas, species diversity is generally lower than in association Ab, averaging 1.25.

As within association Ab, the abundance of *C. arctica* increases upcore, whereas, that of *A. barwonensis* decreases. The decrease in abundance of *A. barwonensis* is steady, with no peaks in abundance; whereas, that of *C. arctica* is uneven. In the early to mid-1960's there was a sudden drop in abundance of *C. arctica* which correlates with a peak in abundance of E. *subconica, P. bartrami,* and *P. sorosa,* as well as a peak in species diversity and drop in foraminiferal abundance. It can be inferred that this was a period when nutrient supply to Midway Bay had been lowered, such that foraminiferal abundance was reduced, and the dominance *C. arctica* had over other species was lessened, allowing secondary species to flourish.

In the mid-1970's a substantial increase in the abundance of *C. arctica* occurred, which provided the basis for a subdivision (by cluster analysis) of the association into two further sub-zones. As in association Ab, the two sub-zones have been mainly separated on the basis of differing abundance of *A. barwonensis* and *C. arctica*. Within the lower zone (sub-zone 1), *A. barwonensis* has an average abundance of 28%, and *C. arctica* of 32%; whereas, in the upper zone (sub-zone 2), *A. barwonensis* has an average abundance of 14%, and *C. arctica* of 54%. Sub-zone 2 has substantially greater foraminiferal abundance than sub-zone 1, averaging 81 specimens/gm sediment in the former, and 12 specimens/gm sediment in the latter. Additionally, the abundance of *E. subconica, P. bartrami,* and *P. sorosa* is significantly greater in the lower zone than in the upper zone.

The abundance of *M. fucsa* generally increases upcore through the association, although there is a major drop in abundance during the mid- to late 1980's which correlates with an increase in *C. arctica*.

11.2.4.3. Foraminiferal palaeoenvironments - conditions and changes

The deeper waters of Midway Bay were occupied by foraminiferal association Ab from 1882 until the early 1950's, after which time it was replaced by association C, which currently occupies the deep waters of the upper estuary. The transition between associations was gradual, and is inferred to have been caused by the increased supply of nutrients to sediments, promoting the abundance of the dominant species of association C (*C. arctica*) over that of association Ab (*A. barwonensis*). Therefore, association Ab became more restricted in distribution during the 20th century, once having originally occupied all deeper subtidal, sandy muds of the upper estuary, and not just the shallow to mid-depth subtidal, muddy sands as it does currently. It is assumed that association C was absent from the estuary before the early 1950's when the nutrient supply of sediments is assumed to have been considerably lower than it is currently.

The changes in fauna along the core reflect implied changing nutrient conditions. Four main periods occur within the core as suggested by the fauna, and these correlate with inferred nutrient supply. Within the lowest sub-zone of association Ab (from 1882 until the mid-1920's), nutrient conditions were probably the lowest recorded; whereas, in the upper sub-zone (from mid-1920's until early 1950's) nutrient supply was likely to be still relatively low, yet two peaks in foraminiferal abundance suggest that nutrient supply had at times increased significantly. In the lower sub-zone of association C (early 1950's until mid-1970's), nutrient supply is again likely to have dropped lower, yet faunal composition remained relatively steady; whereas, in the upper sub-zone (mid-1970's until 2001) nutrient supply is inferred to have increased substantially.

11.2.5. Seafloor environments – changes and links to historical activities

11.2.5.1. Causeway construction (1874)

Since at least 1882, sandy muds have been accumulating in Midway Bay, and probably also in the deeper areas of the upper estuary. A significant increase in the accumulation of mud, compared to sand, in surficial sediments of the area occurred between 1882 and 1907. The timing of this change (as similarly observed by Lane, 2005) follows the construction of the Midway Bay causeway in 1874. Such would have resulted in more stagnant water conditions within Midway Bay, as tidal exchange became more reduced. Consequently, more mud deposition and accumulation occurred in the lowered energy of the environment. Furthermore, the sand transporting capabilities of bottom currents

became more reduced such that less sand transport to the core site from the shoreline could occur.

As the base of the core was dated 1882, the initial increase in mud accumulation following causeway construction is not recorded by the core, such that the total increase in mud accumulation cannot be determined. However, in 1882 at least 8 years had elapsed since the causeway was built, and about 15 years had elapsed since causeway construction began. This would suggest that mud content has probably increased significantly more than has been recorded. Additionally, as mud content has remained relatively consistent during the 20th century (but higher than that of the late 1800's), the causeway has maintained a constant effect upon the seafloor environment of Midway Bay.

There is no evidence that the foraminiferal fauna of the core was affected by the increase in mud content which occurred following construction of the Midway Point causeway. This is expected, as the pH of Midway Bay was already low enough to prevent any calcareous foraminifera from being present. However, it is possible a decrease in pH may still have occurred due to the increase in water stagnation in the area.

11.2.5.2. Richmond weir construction (1930's)

A decline, since the 1930's, in the concentration of dissolved silicate within the waters of Midway Bay, probably indicates an overall decrease in flow entering the upper estuary since the 1930's. This decline was suggested by Lane (2004) to coincide with the construction of a weir at Richmond in the early 1930's. Such would have caused a decrease in flow entering the estuary from the Coal River, as well as an 'averaging' of seasonal flow, leading to a decrease in silicate supply.

11.2.5.3. Nutrient supply and fertiliser usage (20th century)

Since at least 1884, an overall increase in foraminiferal abundance, accompanied by an overall decrease in species diversity suggests that nutrient supply to the sediments of Midway Bay has been increasing. Until the early 1970's this increase appears to have been very gradual, with low foraminiferal abundance suggesting nutrient levels to have been relatively low, yet obtaining small peaks during the mid- to late 1920's and early to mid-1940's. However, a significant increase in nutrient supply (inferred by an increase in foraminiferal abundance) occurred after the early 1970's, reaching a maximum during the early 1990's. Since the 1960's, species diversity has decreased as abundance has increased, suggesting that greater nutrient supply favours certain species over others.

The increase in nutrient supply within sediments in Midway Bay (inferred by the increase in foraminiferal abundance) is likely to be due to the increase in fertiliser (nitrogenous and phosphorus) usage throughout the catchment area during the 20th century. Davies *et al.* (2002) described nutrient delivery to the estuary, sourced by agricultural fertiliser use (via the Coal River sub-catchment), as having increased significantly since European settlement, with phosphorus loads currently 4.4 times higher, and nitrogen loads 2.7 times higher. Australia's shallow marine waters naturally have low nutrient concentrations, with land clearing, grazing and the use of agricultural fertilisers the primary causes of increased catchment nutrient export (Cosser, 1997). During the first half of the 1900's, orchards were established, and remained abundant, with the Pitt Water area, with cropping being the major land use until the 1930's. Fertilisers first came into use in Tasmanian orchards in 1890, with imports increasing after 1896, especially after 1907 (Easteal, 1971). The first significant increase in nutrient supply to Midway Bay is inferred to have occurred in the early 1920's, reaching a minor peak in the mid- to late 1920's, which correlates with a significant increase in $NO_{2\text{-}3}$ levels, and foraminiferal abundance, being indicative of trends in fertiliser usage within orchards at that time.

A subsequent increase in foraminiferal abundance during the 1930's coincides with the introduction of superphosphate to the catchment area, and can be inferred to indicate an increase in nutrient supply. An early to mid-1940's peak in nutrients (inferred by a peak in foraminiferal abundance) correlates with a peak in nitrate levels within sediments, and another peak in foraminiferal abundance, and is likely to be a result of the period of maximum superphosphate and nitrogenous fertiliser usage within the first half of the 20th century.

Low foraminiferal abundance throughout the 1950's to 1960's infers a period of low nutrient supply, and suggests a period of low agricultural activity within the catchment area. The number of orchards had fallen from 130 in 1921, to only 32 in 1952 (DPIWE, 2000). During the 1950's and 1960's, orchards were removed with most land used for grazing of sheep, with some other livestock. In the 1960's, agriculture was in a depressed state and the average farm size of 200 ha was too small to support a family (Daley, 1999).

During 1970's, there was a significant rise in foraminiferal abundance within Midway Bay, inferring a rise in nutrient levels which peaked in the early 1990's. This rise probably reflects increased fertiliser (phosphorus and nitrogenous) usage within agricultural areas during that period, but may also reflect an increase in urban land usage. From 1981 to 1996, there was a rapid increase in the size of townships in the region (DPIWE, 2000). The early 1990's peak in nutrient levels coincides with the establishment in 1990 of the South-

East Irrigation Scheme. The irrigation scheme lead to an expansion of agriculture, with a move from dryland cropping and grazing production to higher value irrigated crops (Foley, 2003). It is worth noting that this peak in nutrient supply occurred despite the Craigbourne Dam having reduced flow to the estuary from the Coal River. This indicates that the amount of nutrient runoff into the Coal River must have been considerably high.

It is uncertain what has caused a dramatic reduction in nutrient levels (inferred by a drop in foraminiferal abundance) since the early 1990's as it is unlikely that fertiliser usage has decreased since then. This identifies a limitation on the correlation used in this chapter between fertiliser usage, nutrient supply and the foraminiferal fauna. However, it is possible that fertiliser is currently more efficiently used in the catchment area. Furthermore, the construction of a second weir on the Coal River in 1992, may have contributed to the drop in nutrient supply by reducing water flow. A drop in dissolved silicate levels during that time may be indicative of such a reduction in water supply (and therefore nutrients) during that time.

To summarise, four main periods of nutrient supply, and hence, fertiliser usage within the catchment area have been identified based upon trends in foraminiferal abundance. During 1882 to mid-1920's, fertiliser usage was relatively low within the catchment area, and hence the supply of nutrients to Midway Bay was also likely to be low. During the mid-1920's to early 1950's, peaks in nutrient supply correlate with the introduction of superphosphate and the dominance of orchards in the catchment area. During the early 1950's to early 1970's, a reduction in agricultural activity is reflected by a foraminiferal fauna of lowered nutrient supply, yet still permanently altered from that before fertilisers were introduced. A substantial increase in fertiliser usage occurred after the early 1970's, reaching a peak in the early 1990's following establishment of the South-east Irrigation Scheme.

11.3. Duckhole Rivulet Core

11.3.1. Introduction

This core was obtained from 0.5 m water depth at the mouth of Duckhole Rivulet within the upper estuary (Figure 10.1). Seven sub-samples were taken from the core, and subjected to sediment, foraminiferal and ostracod analysis. Complete foraminifera and ostracod species lists for each sub-sample are displayed in Appendices F and H, respectively.

11.3.2. Lithostratigraphy

The core is 55.3 cm long, consisting of shell-bearing, grey – brown muddy sand. Sediments are increasingly shelly with depth, with a dense oyster layer occupying the basal two thirds of the core.

11.3.2.1. Core dating and sedimentation rates

^{210}Pb analysis dated the base of the core at 1919 (with an error margin of 2.2 years), and a constant sedimentation rate of 0.575 cm/year was calculated for the core, providing the basis for calculation of the age data displayed in Table 11.2 (Mitchell et al., 2005). A problem which arises from the ^{210}Pb dating technique is the assumption of a constant sedimentation rate. In the Duckhole Rivulet core, a constant sedimentation rate is assumed in order to produce a timeline; however, it is likely that the actual sedimentation rate did vary to some extent. This is indicated by the presence of a dense oyster layer, probably representing a period of low sedimentation, which allowed oyster growth to occur. An increase in sedimentation rate probably occurred above this layer. Therefore, the timeline constructed for the core needs to be used more as a general chronological guide, rather than a detailed timeline.

Depth (cm)	+/- years	Corrected age	Corrected year
0.5	Mixed surface layer (2001)		
3.5			
6.5	0.9	5	1997
12.5	0.9	16	1986
24.0	1.9	36	1966
51.0	2.2	83	1919

Table 11.2. ^{210}Pb chronology of the Duckhole Rivulet core (from Mitchell et al., 2005).

11.3.2.2. Particle-size distribution

The muddy sands of the core have a mud content ranging from 14 to 39% (averaging 25%), which is typical for the modern shallow subtidal sediments of the area. From the early 1920's until the late 1970's, mud content gradually decreased from 39% to 14% (Figure 11.6). Mud content was relatively consistent between the late 1970's and mid-1990's, but increased from 15% in the mid-1990's to 33% in 2002.

Generally, terrigenous sand ranges from very fine to coarse grade, averaging fine grade. Very fine sand is gradually more abundant upcore, whereas, the abundance of fine sand varies inversely to that of mud content. Very coarse sand and granule/pebble grades are represented by the shell content of the sediments, being more abundant with depth, and most abundant (20 – 50% granules/pebbles) within the oyster layer. Consequently, the abundance of the granule/pebble fraction provides an index to the shell content of the sediments.

11.3.2.3. Sand characteristics

Lithic sand content is consistently 40-50% throughout the core, which is similar to that of modern surficial sediments in the area. The terrigenous sand content is moderately well sorted, and grains are generally angular to very angular.

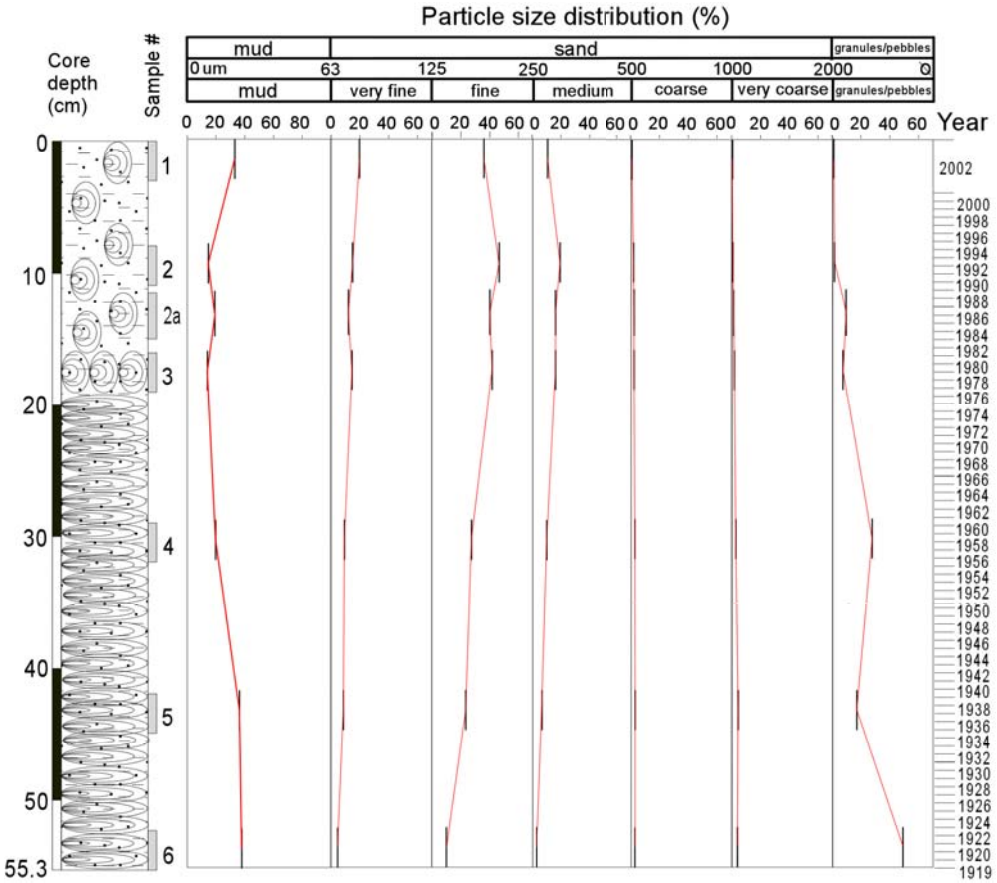

Figure 11.6. Duck Rivulet core - particle-size distribution data.

11.3.2.4. Shell content

The core can be divided into four zones according to shell content. The first is a dense oyster layer, which occupies the basal two-thirds of the core, ranging from 55.3 – 19 cm, corresponding with the early 1920's to the mid-1970's. This layer consists mainly of the native flat oyster, *Ostrea angasi*, but also contains minor clams (mainly *Notospisula trigonella*) and gastropods. *Ostrea angasi* still occurs in low numbers within the estuary, but not in beds of such considerable density. There is evidence of mixing within the oyster layer, particularly below 34 cm depth; however, clams and gastropods appear to be more common upcore.

From 19 cm to 16 cm depth (mid-1970's to early 1980's), a highly shelly clam layer occurs. This relatively dense shell layer consists mainly of *Notospisula trigonella*, but also contains other clam species and gastropods. The layer has a relatively sharp boundary with the underlying oyster layer, and contains no oyster shells.

From 16 cm to the surface (early 1980's to 2002), shell content still consists mainly of clams with minor gastropods, but the total shell content is considerably less, and decreases upcore. Two further sub-zones were identified within this zone: a moderately shelly layer from 16 - 11 cm depth (early 1980's to late 1980's), and above this, a slightly shelly layer (late 1980's to 2002). There is a transitional boundary between both of these shell layers, however, there is a marked difference in shell content between them.

11.3.2.5. Plant material

Some sediments contain the remains of plant material, either of terrigenous origin, transported to the site of deposition by fluvial flow, or aquatic vegetation which grew at the site. Due to the small, broken nature of the material, identification was difficult; however, seagrass and woody fragments were identified.

Within the oyster layer, plant material was largely absent, although some woody fragments were present. Within the highly shelly clam layer, plant material was slightly more noticeable; however, above this layer, plant material was relatively common, consisting of both woody and seagrass remains. The increase in plant material upcore is probably the combined result of increased delivery of plant matter by fluvial flow, and increased seagrass growth which followed the significant reduction in the shell content of sediments.

11.3.2.6. Depositional environments

An overall decrease in the shell content of muddy sands within the mouth of Duckhole Rivulet has occurred during the 20th century. This change in shell content initially occurred with the disappearance, in the mid-1970's, of a dense oyster layer, and its replacement by a less dense clam layer containing minor gastropods. By the early 1980's, clam (and gastropod) shell content had also begun to decrease, with the slight shell content of modern sediments reached in the late 1980's. With the upcore loss in oyster shell content, mud content also decreased. An increase in mud content since the mid-1990's, correlates with the decrease in clam shell content.

Possibly the most important change within the core, is the abrupt transition from a dense native oyster layer to a relatively dense clam layer. Oysters have been referred to as the 'canary of the estuary' as a decline in their health presents an early warning sign of river health problems (HRC, 2003). The most critical factors influencing all stages of oyster development are water temperature, dissolved oxygen, salinity, suspended material concentration (turbidity) and pH (Shumway, 1996). Changes in salinity and water temperature are not indicated by faunal changes within core. Being a euryhaline species, *Ostrea angasi* can tolerate changes in salinity and temperature (and such changes have not been indicated by fauna within the core). Of the remaining factors, turbidity is perhaps the most likely to have lead to the disappearance of the native oyster bed. It was observed in the modern estuary that turbid waters in the Pacific oyster growing areas have a significant inhibitory effect on oyster growth (Crawford and Mitchell, 1999). Pacific oysters appear able to survive and grow in more highly turbid waters than other [native] oysters (Hone, 1996). Therefore, it is likely the abundance of native oysters is low within the modern estuary compared to that of Pacific oysters, mainly as a result of high turbidity.

Clams occupy a broader range of habitats than oysters, and are able to settle on a variety of substrates (mud, sand, gravel), burying themselves into the sediment; whereas, oysters settle on a more restricted range of substrates, attaching mainly to rock and shell (Gosling, 2003). Consequently, bivalves (such as oysters) which are 'attached surface dwellers', do not possess physiological features, such as mantle fusion and siphons, which allow 'soft-bottom burrowers' (such as clams) the ability to reduce the intake of sediment (Dorit et al., 1991). In oysters, increased concentration of suspended materials can induce a reduction in pumping rate, a clogging of the gill apparatus, a subsequent reduction in growth rate, and death (Shumway, 1996). Therefore, at the core site, an increase in water turbidity may have caused the decline in native oysters, and an increase in abundance of clams, due to the

greater ability of the latter to cope with higher turbidity. Once the oysters had disappeared, a niche opened up for the clams to occupy, as they had only previously inhabited the restricted areas of sediment between oyster shells.

A change in water quality is likely to have accompanied the increase in turbidity which lead to the end of oyster growth within the mouth of Duckhole Rivulet during the mid-1970's. An increase in sedimentation is likely to have accompanied increased turbidity. Even a thin film of silt can markedly reduce oyster settling, and increased sedimentation may kill oysters by smothering them (HRC, 2003). Lowered dissolved oxygen and pH, caused by increased nutrient supply carried by turbid river waters, could also have contributed to the demise of the oyster bed.

After the early 1980's, there was a reduction in clam (and gastropod) shell content of sediments, correlating with increased plant material content. The increase in plant content is indicative of two changes: firstly, that seagrass growth had begun upon the less shelly substrate; and secondly, that there was increased delivery of organic material derived from the catchment area. As observed in the modern estuary, an increase in the delivery of dissolved and particulate nutrients can lead to a lowering of dissolved oxygen concentrations, which may cause a reduction in pH. A progressive lowering in bottom water pH could have caused the progressive loss of shell content in sediments of the core. This is supported by signs of increasing calcareous dissolution upon clam shells, further upcore as total shell content decreases, being most severe by the late 1980's, when the shell content of sediments was only minor.

11.3.3. Fossil foraminiferal distribution and facies

11.3.3.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is low, with Fisher α indices ranging from 1.5 to 3.1, averaging 2.4. Species diversity increases upcore overall (Figure 11.7). Apart from one anomalous value, diversity within the oyster layer is lowest, being marginally greater in the highly shelly clam layer, and greatest within the moderately and slightly shelly clam layers. The overall increase in species diversity upcore suggests that conditions have become favourable for a greater number of species of foraminifera within the mouth of Duckhole Rivulet since the early 1920's. It also suggests that within the oyster layer, the foraminifera were dominated by a smaller number of species.

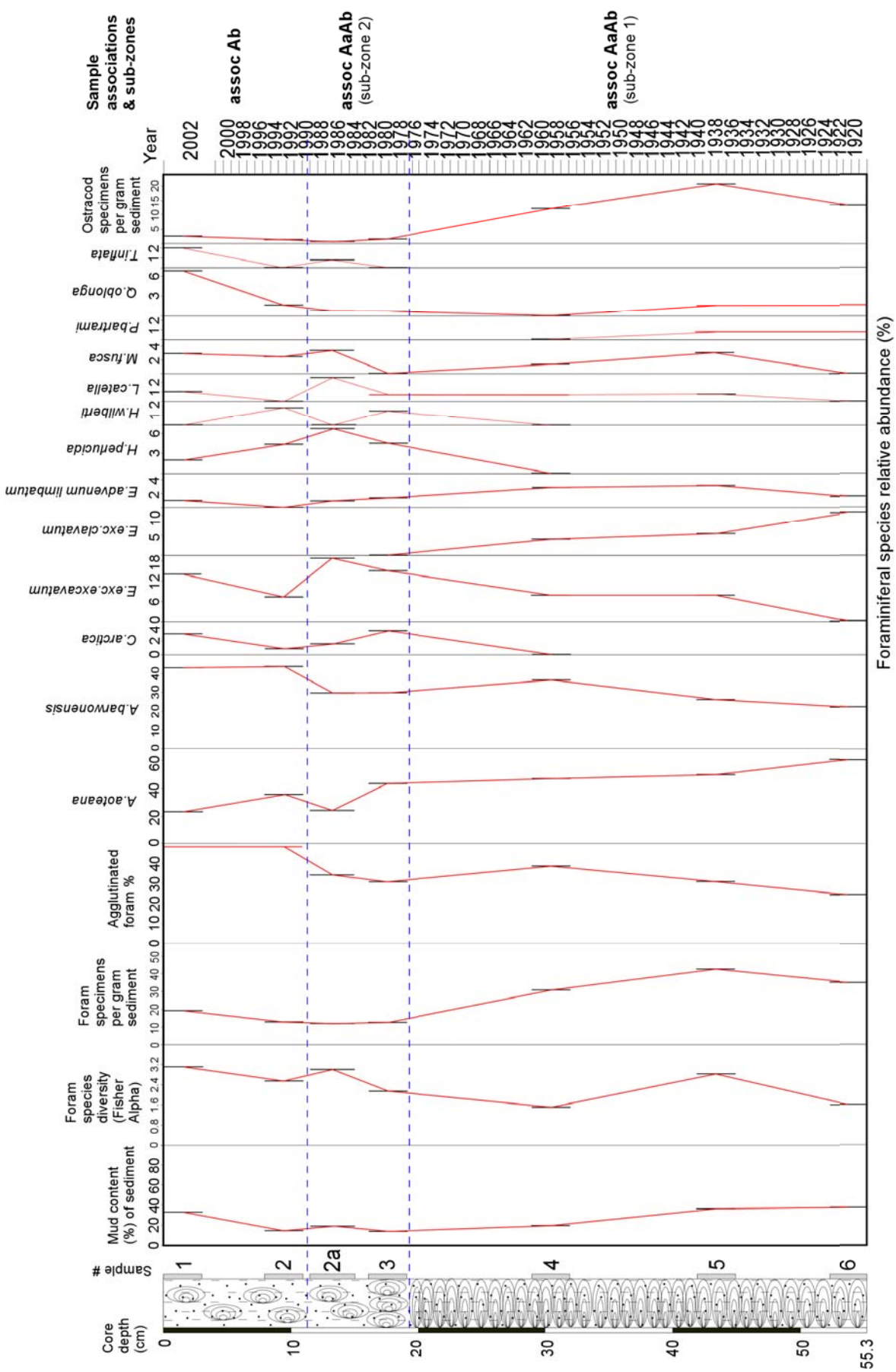

Figure 11.7. Fossil foraminiferal distribution in the Duckhole core.

(ii) Abundance

Foraminiferal abundance is generally low, ranging from 13 to 42 specimens per gram of sediment, and averaging 24. Overall, abundance decreases upcore, being significantly more within the oyster layer (31 – 42 specimens/gm sediment) than in the overlying sediments (13 – 19 specimens/gm sediment). The greater abundance of foraminifera within the oyster layer suggests that conditions then were more favourable for population growth. It is also possible that a greater accumulation of foraminiferal tests was possible during that time due to the slow accumulation of oyster shell material.

(iii) Agglutinated Foraminifera

The abundance of agglutinated foraminifera increases upcore within the core from 24% at the base to 48% at the top. This increase is relatively gradual, yet between the late 1980's and early 1990's there is an abrupt increase from 34% to 48%. Agglutinated content then remained at 48% until 2002.

In the modern estuarine environment, it has been observed that agglutinated foraminiferal content is largely correlated to bottom water pH, and, to a lesser extent, salinity. In lowered pH conditions, calcareous test dissolution can occur, thereby favouring a greater abundance of agglutinated species. The lowering of water pH is a consequence of the lowering of dissolved oxygen caused by either water stagnation, or high levels of dissolved and particulate nutrients. Additionally, as more agglutinated species tend to prefer lower salinity conditions within the estuary, greater agglutinated content can, to some degree, be indicative of greater freshwater influence.

Consequently, an agglutinated content ranging from 24% to 48% is indicative of pH conditions ranging from high to intermediate, with intermediate-high pH occurring in the area from at least the early 1920's until the late 1980's, and intermediate pH occurring since the late 1980's. Within the oyster layer, agglutinated content suggests that pH decreased upcore; whereas, between the highly and moderately shelly clam layers (from mid-1970's until late 1980's), agglutinated content increased slightly, suggesting that pH decreased slightly, then remained consistent until the current day. Therefore, although the overall change in agglutinated content from the bottom to the top of the core is only 24%, it is still sufficient to be indicative of the progressive decrease upcore in clam, oyster and gastropods content of the sediments.

11.3.3.2. Sample associations and sub-zones

A combined cluster analysis of all Duckhole Rivulet core sub-samples and modern surficial samples (used for cluster analysis in chapter 7) identified, within the core, the new foraminiferal sample association AaAb between the early 1920's and late 1980's, and association Ab between the late 1980's and 2002 (Figure 11.7). Sample association AaAb could be further divided into sub-zones 1 and 2.

It is mainly the opposing abundance of *Ammonia aoteana* (decreasing upcore) and *Ammobaculites barwonensis* (increasing upcore) which provides the major trend in species composition, forming its subdivision into associations. Within association AaAb, the abundance of *A. aoteana* and some secondary species define the presence of the two sub-zones.

(i) Association AaAb

General characteristics and faunal composition of the new association

Before describing the occurrence of association AaAb within the Duckhole Rivulet core, the general characteristics and species composition of this new foraminiferal sample association need to be described. Table 11.3 summarises this information based upon the occurrence of the association in sub-samples of the Duckhole Rivulet, Samphire Island and Stinking Point cores. The association no longer exists within the modern estuarine environment, but the species it contains are still present. Association scores for species of the association are summarised in Appendix G.

Mud content (%)	**Abundance** (specimens/gm sediment)	**Species diversity** (Fisher α)	**Agglutinated content** (%)	**Cores present in**
22 *(14 – 39)*	15 *(3 – 42)*	Low 1.6 *(0.8 – 3.0)*	36 *(24 – 50)* implied pH = intermediate - high	Duckhole Samphire Is. Stinking Pt.
Species		**Relative abundance** (%)	**Species**	**Relative abundance** (%)
Ammonia aoteana		49 *(34 – 61)*	*Leptohalysis catella*	0.43 *(0 – 2.5)*
Ammobaculites barwonensis		33 *(23 – 42)*	*Quinqueloculina oblonga*	0.43 *(0 – 1.6)*
E. excavatum clavatum		6.6 *(0 – 27)*	*Haplophragmoides wilberti*	0.38 *(0 – 1.8)*
E. excavatum excavatum		5.3 *(0 – 19)*	*Paratrochammina bartrami*	0.15 *(0 – 0.8)*
Trochammina inflata		1.5 *(0 – 6)*	*Quinqueloculina seminula*	0.09 *(0 – 0.9)*
Aubignyna perlucida		0.9 *(0 – 7)*	*Textularia earlandi*	0.08 *(0 – 0.9)*
E. advenum limbatum		0.9 *(0 – 3)*	*Bolivina doniezi*	0.07 *(0 – 0.8)*
Miliammina fusca		0.8 *(0 – 3.4)*	*E. excavatum williamsoni*	0.07 *(0 – 0.8)*
Cuneata arctica		0.5 *(0 – 3.6)*		

Table 11.3. General characteristics and species composition of sample association AaAb.

The association has low abundance and low species diversity, typical of the shallow subtidal areas of the upper estuary from which cores containing the association were obtained. Although essentially a 'mixed agglutinated and calcareous' association, calcareous foraminifera are always dominant. This implies that pH conditions vary between intermediate and high, which in the upper estuary, currently occur only within the intertidal zone. This indicates that the association represents a shallow subtidal environment of the upper estuary where pH was once significantly higher than it is today.

The association is co-dominated by *A. aoteana* and *A. barwonensis*, with the former always more abundant. These species are euryhaline, tolerant of a wide range of salinity, yet preferring similar brackish to very slightly brackish salinity. In the upper estuary, the distribution of *A. aoteana* is limited by low pH conditions, with the species being restricted to shallow subtidal – intertidal depths, within which it occurs in relatively low numbers. In contrast, due to the low pH, *A. barwonensis* is abundant in the shallow subtidal depths of the upper estuary. Therefore, the high abundance of *A. aoteana* in the association, and its dominance over *A. barwonensis*, is indicative of similar salinity and water depth to that in which the cores were obtained, yet higher pH conditions than in which they currently occur.

The most abundant three calcareous species of the association, *A. aoteana*, *E. excavatum excavatum* and *E. excavatum clavatum*, are still the most common calcareous species in the shallow subtidal areas of the upper estuary, being the calcareous species most tolerant of lower salinity. Of these, *E. excavatum excavatum* is the most tolerant to lower salinity. Tolerance to lowered pH is also common to each species, although *A. aoteana*, and particularly, *E. excavatum excavatum*, are the calcareous species most tolerant to lowered pH. The minor species in the association are all currently found in shallow subtidal or intertidal depths within the upper estuary, and are indicative of similar salinity conditions to that indicated by the main species.

Presence of the association within the Duckhole Rivulet core

Association AaAb represents the major, lower portion of the Duckhole core in sediments dating from the early 1920's to the late 1980's. Within the core, the association is co-dominated by *A. aoteana* (average abundance of 47%) and *A. barwonensis* (29%) with minor *E. excavatum excavatum* (9.5%) and *E. excavatum clavatum* (4.2%). Secondary species include *H. perlucida, E. advenum limbatum, M. fucsa, C. arctica* and *Q. oblonga*. Specimen abundance ranged from 13 to 42 specimens/gm sediment, averaging 27. Species diversity is low, with the Fisher α Index averaging 2.2.

The abundance of *A. barwonensis* increases upcore overall within the association, suggesting that pH levels are decreasing gradually. Following this trend, the abundance of *A. aoteana* decreases gradually upcore as *A. barwonensis* decreases. The abundance of *E. excavatum excavatum* increases, and *E. excavatum clavatum* decreases, upcore within the association. It has been observed earlier in this study that the former species is more tolerant of lowered pH than the latter species. This species is also an indicator of greater freshwater influence. However, as more upstream areas of the modern estuary tend to contain lower pH waters, it may be that a decrease in pH in such areas produces an increase in abundance of species such as *E. excavatum excavatum* which are normally indicators of greater freshwater influence. Therefore, such may be a further indication of decreasing pH levels upcore within the association.

During the mid-1970's, a change occurs in faunal composition, characterised by the disappearance of *E. excavatum clavatum*, an abrupt increase in *E. excavatum excavatum*, and the appearance of some secondary species, such as *C. arctica, H. perlucida, H. wilberti* and *T. inflata*. There is no significant change in agglutinated content, but both *A. aoteana* and *A. barwonensis* decrease in abundance. This change coincides with the end of the oyster layer and an abrupt drop in ostracod abundance, and was identified by cluster analysis as separating the association into lower sub-zone (1) and an upper sub-zone (2).

Within the lower sub-zone (1), foraminiferal abundance is much greater than in the above zone, and mud content is also greater. Agglutinated content and the abundance of *A. barwonensis* and *E. excavatum excavatum* increase upcore within the sub-zone; whereas, the abundance of *A. aoteana* and *E. excavatum clavatum* decrease.

Within the upper sub-zone (2), agglutinated content and mud content increase slightly, and clam and gastropod shells become less abundant within sediments. *E. excavatum excavatum, H. perlucida, L. catella*, and *M. fucsa* each increase in abundance upcore, reaching a peak within the moderately shelly layer (mid- to late 1980's).

(ii) Association Ab

Association Ab represents the upper portion of the core, in sediments dating from the late 1980's until 2002. This association currently occupies most of the shallow subtidal zone throughout the upper estuary. In the core, the association is dominated by *A. barwonensis* (average abundance of 44%) with sub-dominant *A. aoteana* (30%), and secondary *E. excavatum excavatum* (11%). Minor species include *Q. oblonga, H. perlucida, M. fucsa* and *C. arctica*.

Specimen abundance is similar to that of the underlying sub-zone, averaging 16 specimens/gm sediment; whereas, species diversity is slightly higher, with an average Fisher α index of 2.8. Mud content increases upcore from 15% during the early 1990's to 33% in 2002, with a correlating increase in foraminiferal abundance.

Agglutinated content is significantly greater than in the underlying association, indicative of lower (intermediate) pH conditions. The abundance of the major agglutinated species, *A. barwonensis*, is also significantly greater than in the underlying association. Within the association, the abundance of this species remains consistent; however, there is a significant decrease upcore in the abundance of *A. aoteana* and *H. perlucida*, and a significant increase in *E. excavatum excavatum* and *Q. oblonga*. The increase in abundance of *E. excavatum excavatum* is further indication of decreasing pH levels.

11.3.3.3. Foraminiferal palaeoenvironments - conditions and changes

The shallow subtidal waters within the mouth of Duckhole Rivulet were from the early 1920's until the mid-1970's the site of a dense oyster bed. This oyster bed contained a foraminiferal association AaAb (sub-zone 1) indicative of similar salinity to that in the area today, yet significantly higher pH conditions (intermediate-high) than those that currently occur there. Gradually decreasing pH is indicated by the fauna as occurring upcore within the oyster layer, probably resulting from lowering dissolved oxygen levels, due to either increased water stagnation and/or the increased supply of nutrients.

When the oyster bed disappeared in the mid-1970's, a relatively dense clam layer appeared, and the foraminiferal fauna of association AaAb changed to sub-zone 2, mainly by the disappearance of *E. excavatum clavatum* and increase in *E. excavatum excavatum* (due to a greater tolerance by the latter species to lowered pH), and the first appearance of some secondary species. There was also a dramatic reduction in foraminiferal abundance. From then until the late 1980's, as clam shell content decreased, a further lowering of pH levels occurred, as indicated by a slight increase in agglutinated foraminifera and further changes in species composition. However, agglutinated content indicates the pH to have still been generally intermediate – high.

After the late 1980's, a significant change occurred in foraminifera, correlating with a further reduction in clam shell content. The foraminiferal association AaAb disappeared from the area (and probably most of the upper estuary), being replaced by association Ab, which, with the abrupt increase in agglutinated content, is indicative of lower (intermediate) pH conditions. Further species changes have occurred since then which, as

the agglutinated content hasn't changed, are possibly a result of the increase in mud content of sediments.

11.3.4. Fossil ostracod distribution and facies

11.3.4.1. Trends in general characteristics

(i) Diversity

Species diversity is low-medium, with Fisher α indices ranging from 1.5 to 4.3, averaging 3.3. Species diversity decreases upcore overall, being relatively consistent (Fisher α indices of 3.5 – 4.3) from the early 1920's until the early 1980's, but decreasing steadily from then until having a Fisher α index of only 1.5 in 2002 (Figure 11.8). This trend follows the upcore decrease in shell content of sediments, being greatest in the oyster and highly shelly clam layers, intermediate in the moderately shelly layer, and least in the slightly shelly layer. Such indicates that the lowering pH responsible for decreasing shell content reduced the diversity of ostracods within the core.

(ii) Abundance

The abundance of ostracod specimens is significantly greater (11 – 17 specimens/gm sediment) within the oyster layer than elsewhere in the core (< 2 specimens/gm sediment). The density of the oyster layer indicates that conditions were suitable for the accumulation of shell material, possibly due to the better water quality (low turbidity, intermediate-high pH) and less mud deposition. Consequently, more ostracod (and foraminiferal) shells accumulated probably as a result of there being a greater living population, as well as the accumulation of the tests of dead individuals.

11.3.4.2. Sample associations and sub-zones

A combined cluster analysis of all Duckhole Rivulet core sub-samples and modern surficial samples (used for cluster analysis in chapter 7) identified only ostracod sample association Mp within the core. However, three further sub-zones were identified within the core: sub-zone 1 (early 1920's to early 1980's), sub-zone 2 (early 1980's to late 1980's, and early 1990's to mid-1990's), and sub-zone 3 (mid-1990s to 2002) (Figure 11.8). These sub-zones are mainly distinguished using the abundance of *M. portjacksonensis* (with peaks in abundance identifying sub-zone 2) although the abundance of other species is also important in their identification.

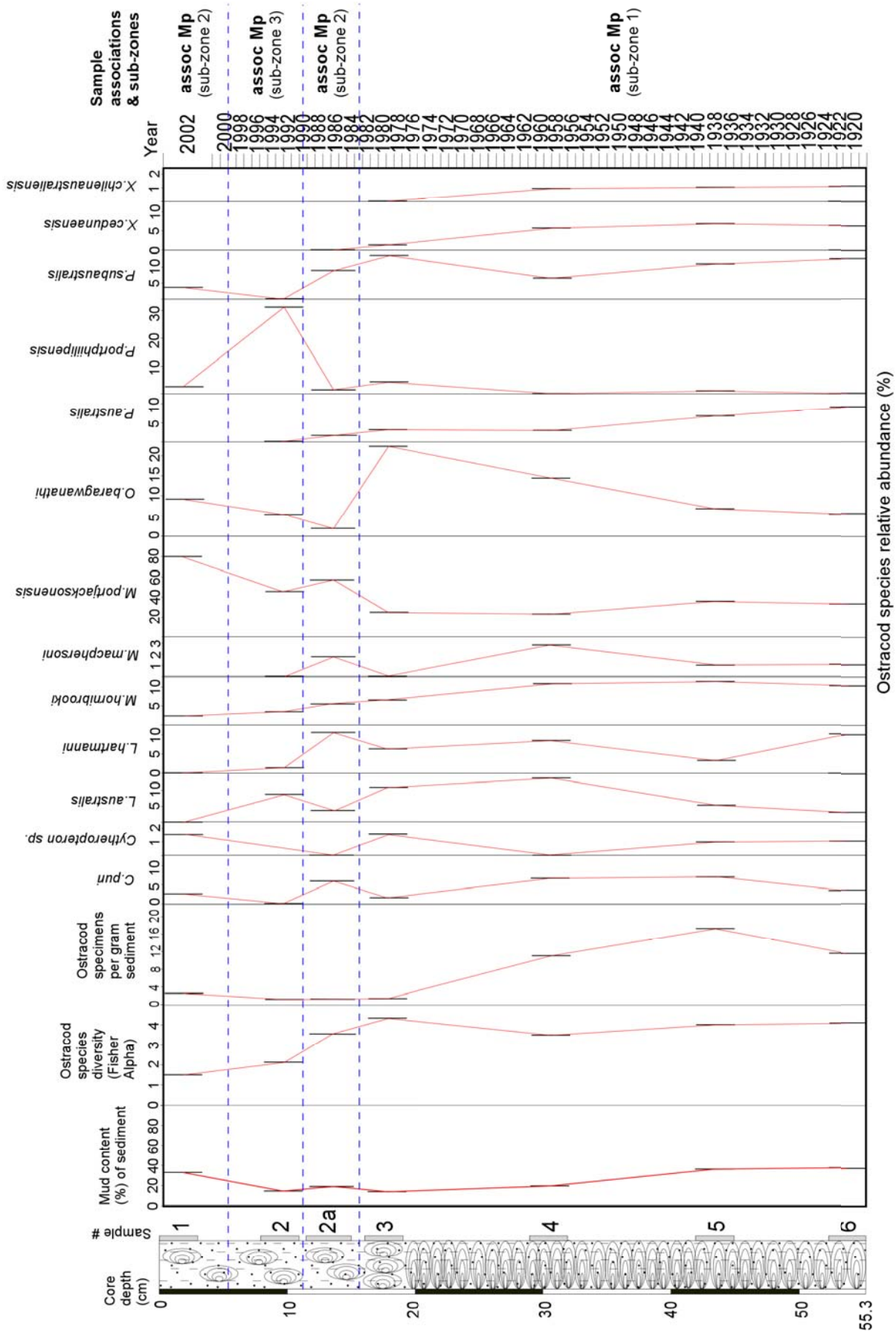

Figure 11.8. Fossil ostracod distribution in the Duckhole core.

(i) Association Mp

The shallow subtidal depths of the upper estuary are currently occupied by association Mp. Therefore, the presence of the association throughout the Duckhole Rivulet core indicates that it has been present in the area since at least the 1920's.

The association is dominated by *M. portjacksonensis* (average abundance of 43%), with secondary *O. baragwanathi* (9%), *P. subaustralis* (8%), *M. hornibrooki* (8%), *L. australis* (7%), *L. hartmanni* (6%) and *P. portphillipensis* (6%).

Sub-zone 1 runs from at least the 1920's until the early 1980's, occupying the oyster and highly shelly clam layers. Many species have greater abundance within this sub-zone than in the subsequent sub-zones, reflecting the higher diversity and abundance within the shellier sediments. However, the abundance of *M. portjacksonensis* is significantly less than in the overlying sub-zones. Within sub-zone 1, important changes occur upcore with certain species. *O. baragwanathi* and *P. subaustralis* steadily increase in abundance upcore, whereas, *P. australis, X. cedunaensis* and *X. chilensis austrocontinentalis* decrease. In chapter 8 it was noticed that within association Mp the distribution of some species reflected areas of differing marine and freshwater influence, with *P. subaustralis* and *O. baragwanathi* significantly more abundant within the mouth of the Coal River; whereas *P. australis* and *X. cedunaensis* were most common within the most downstream sample. *O. baragwanathi* was also noted to be restricted to areas of greater freshwater influence, and to be tolerant of low levels of dissolved oxygen. If (as discussed in the previous section on foraminifera) pH conditions have decreased slightly upwards along the oyster layer, but the degree of freshwater influence has remained more or less steady, then an increase in abundance of species which indicate increasing proximity to fluvial flow in the modern environment, may in fact to be indicative of declining pH, as low pH is currently common in such areas. Therefore, the changing species composition upcore within sub-zone 1 is indicative of steadily declining pH conditions.

It also needs to be considered that *O. baragwanathi* and *P. subaustralis* may have a preference for shelly sediments when pH levels are raised, in particular, for the highly shelly layer. Alternatively, as both are the largest ostracod species found in the estuary, a size sorting process may be accounting for their higher abundance in shelly sediments.

Sub-zone 2 occurs over two sections of the cores separated by sub-zone 3. Within the lower section of sub-zone 2, the abundance of *M. portjacksonensis* is substantially higher than in sub-zone 1, *O. baragwanathi* and *P. subaustralis* are less abundant, and *X. cedunaensis* is absent. The abundance of ostracods is as low as it was within the underlying

highly shelly clam layer, yet species diversity has decreased significantly. Within the upper section of sub-zone 2, *M. portjacksonensis* is even more abundant, and many other species are less abundant or absent, with species diversity having decreased even further. The high abundance of *M. portjacksonensis* within sub-zone 2, and its increasing abundance upcore is indicative of decreasing pH conditions, as it is the ostracod species most tolerant of low pH. However, it may also be indicative of increasing turbidity. Certain species tolerant of reduced pH, such as *O. baragwanathi* and *P. subaustralis*, increased in abundance upcore within sub-zone 1 as pH decreased, yet by sub-zone 2 lowered pH exceeded the limits in which such species could remain abundant.

Sub-zone 3 is similar in species composition to sub-zone 2, except for the high abundance of *P. portphillipensis* (32%), a species which was rare elsewhere in the core. This species is known, from its distribution within the modern estuary, to be indicative of seagrass, and therefore indicates that seagrass increased significantly after the early 1990's (possibly due to the less shelly substrate). The near-absence of the species in the core by 2002 indicates that seagrass had either declined dramatically by then, or that pH had become too low for the species to remain abundant.

11.3.4.3. Ostracod palaeoenvironments - conditions and changes

The shallow subtidal waters within the mouth of Duckhole Rivulet have contained ostracod association Mp since at least the early 1920's. This association currently occupies most of the subtidal zone of the upper estuary, occurring in areas of muddy sand with low pH and high turbidity.

Initially, ostracod abundance and species diversity were considerably higher than they are currently. The abundance of ostracods dropped abruptly after the oyster layer ended (mid-1970's), and species diversity began a steady decline after the early 1980's when clam shell content began to decline.

Many changes in species composition appear related to declining pH conditions occurring upcore. Sub-zone 1 (1920's to early 1980's) occupied both the oyster and highly shelly clam layers, and the changing abundance of some species indicates that pH decreased upcore within these shell layers; however, the first major change in species composition correlated not with the ending of the oyster layer (as with foraminifera), but with the ending of the highly shelly clam layer.

After the early 1980's, pH declined more rapidly, as demonstrated by the steady increase in abundance of *M. portjacksonensis,* and continuing decline in species diversity.

During this period, two ostracod sub-zones (1 and 2) define a period during the late 1980's to mid-1990's when seagrass was abundant. Seagrass still occurs in the area today, but was probably more abundant during that time. The emergence of seagrass during that period may have been a result of a less shelly substrate. The decline in seagrass density after the mid-1990's can be linked to increased water turbidity, as indicated by the increased abundance (since the mid-1990's) in *M. portjacksonensis*.

11.3.5. Seafloor environments – changes and links to historical activities

11.3.5.1. Early agricultural activity (1920's to mid-1970's)

Many of the changes in lithology and benthic species composition within the core can be linked to agricultural activities which occurred within the catchment area. From the early 1920's to the mid-1970's a dense oyster bed occupied the shallow subtidal waters within the mouth of Duckhole Rivulet. This layer supported a high abundance and diversity of benthic species and represented a period when pH conditions were intermediate – high, and sedimentation was low.

The abundance of orchards, and other agricultural land use, within the catchment during the first half of the 20th century is likely to have caused to an initial increase in turbidity within the core site, as well as gradual increase in sedimentation and the delivery of increased nutrients. Such changes in water quality are indicated within the oyster layer by changes upcore in foraminifera and ostracods, and by a gradual increase in abundance of clams and gastropods. During this time, dissolved oxygen concentrations and pH levels declined slightly, turbidity increased, and sedimentation is likely to have increased. However, it was only by the mid-1970's that water turbidity had become high enough that oyster growth could no longer be maintained in the area.

11.3.5.2. Increased agricultural activity (mid-1970's to late 1980's)

The Midway Bay core indicated that an increase in agricultural activity and fertiliser usage within the catchment area during the early 1970's had a dramatic effect upon foraminifera, by the increased supply of nutrients. Within the Duckhole Rivulet core, the cessation of the oyster layer in the mid-1970's, and its replacement by a relatively dense clam layer, indicates that turbidity had become high enough to inhibit oyster growth, allowing the more tolerant clams to proliferate. This indicates that the increased delivery of suspended sediment to the area, resulting from increased agricultural activities, had reached a critical limit for tolerance by native oysters in the area (the abundance of

foraminifera and ostracods also fell dramatically at this time). However, it is also likely that the additional detrimental effects of declining water quality (increased sedimentation, lowering dissolved oxygen and pH) also contributed to the demise of native oysters.

From the mid-1970's to the late 1980s, gradually declining pH, caused by declining oxygen concentrations, resulting from increased nutrient delivery to the area, caused increasing calcareous shell dissolution, which lead to a steady decline in clam shell content within the sediments, as well as a change in foraminiferal and ostracod species composition. The increase in nutrient delivery is likely to be a result of increasing fertiliser usage (as similarly indicated by the Midway Bay core). The increased abundance of plant material within sediments after the early 1980's is further indication of increased delivery to the area of material derived from the catchment.

11.3.5.3. Agricultural activity after the South-east Irrigation Scheme (early 1990's to 2002)

After the establishment of the South-east Irrigation Scheme in the late 1980's, an abrupt lowering of bottom water pH levels occurred to the seafloor environment at the mouth of the Duckhole Rivulet. This was probably a result of the increased delivery of nutrients derived from increased fertiliser usage in the catchment area, following the increase in higher value irrigated cropping. However, it may also be partly a consequence of increased water stagnation following construction of the Craigbourne Dam in 1985.

By the early 1990's, clam shell content was reduced to only minor amounts within sediments. The less shelly substrate allowed seagrass to become further established in the area, however, after then seagrass density became reduced, probably as a result of increased nutrients and turbidity.

The foraminiferal fauna since the early 1990's, has been indicative of intermediate pH conditions within the area. However, since that time, changes in ostracod species composition are suggestive of a further increase in water turbidity, possibly resulting from the increase in water stagnation following construction of the Craigbourne Dam, or an increase in suspended sediment delivery following increased agricultural activity which occurred after the South-east Irrigation Scheme was established.

11.4. Samphire Island core

11.4.1. Introduction

This core was obtained in 0.5 m water depth within the Coal River, adjacent to Samphire Island (Figure 10.1). Fifteen sub-samples were taken from the core and subjected to sediment, foraminiferal and ostracod analysis (Appendices F, H).

11.4.2. Lithostratigraphy

The core is 127.5 cm long, consisting mainly of grey muddy sand, yet containing sandy mud at mid-depth, and a clam shell layer within the lower half.

11.4.2.1. Core dating and sedimentation rates

Excess ^{210}Pb activity was near background levels below 60.5 cm, making dating of the core below that depth impossible by the technique, yet the date at that depth was 1963, with an error margin of 8 years (Mitchell et al., 2005). Consideration of the error range (in years) for each sample dated (Table 11.4), means that the timeline constructed for the core is used more as a general chronological guide, rather than a detailed timeline. A constant sedimentation rate of 1.355 cm/year was calculated for the core, providing the basis for calculation of the age data displayed in table 11.4 (Mitchell et al., 2005). As there are no age data for the core below 60.5 cm depth, that section of the core will be referred to by depth (cm) rather than age (years). A mixing depth of 7.5 cm was calculated.

Depth (cm)	+/- years	Corrected age	Corrected year
0.5	Mixed surface layer (2001)		
3.5			
7.5			
12.5	1.7	4	1998
36.5	4.8	21	1981
60.5	8.0	39	1963

Table 11.4. ^{210}Pb chronology of the Samphire Island core (from Mitchell et al., 2005).

11.4.2.2. Particle-size distribution

The sediments of the core have a mud content which ranges from 14 to 89%, averaging 30%. From the base of the core until the late 1960's, sediment was muddy sand with a mud

content remaining consistently low at between 14 and 24% (Figure 11.9). However, after the late 1960's, mud content rose abruptly such that sandy mud was present (with a mud content of 89%) in the early 1970's until the early 1980's, with muddy sand present thereafter. Mud content decreased from the early 1970's until 2002, with this decrease greatest while sandy mud was present, and only gradual thereafter. However, there was a minor rise in mud content during the early to mid-1990's.

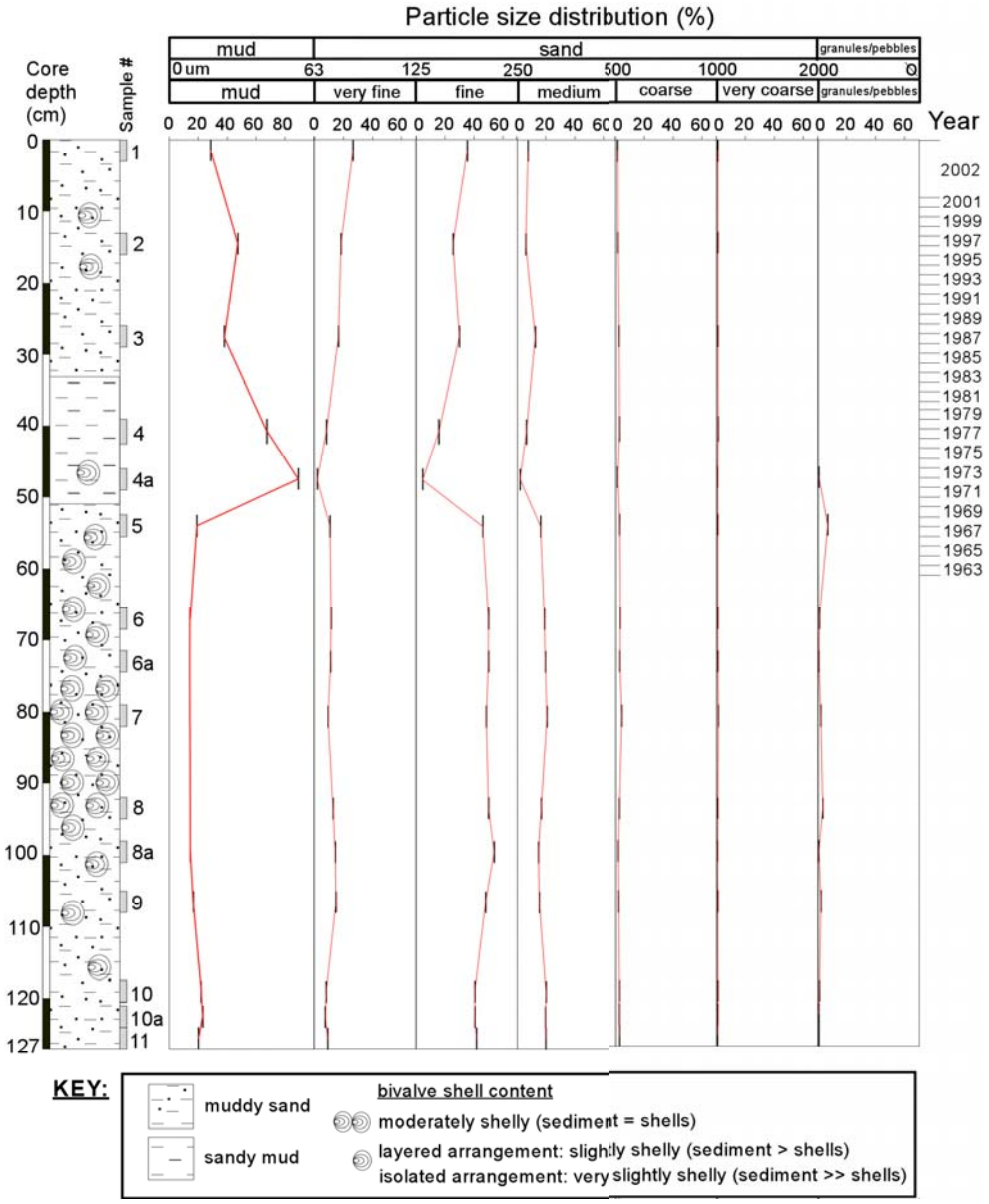

Figure 11.9. Samphire Island core - particle-size distribution data.

The most abundant sand fraction in all sub-samples was 125 – 250 μm, indicating that sand has consistently been of fine grade. As in the Duckhole Rivulet core, variations in the

proportion of sand are inverse changes in mud content; this is most apparent with the proportion (%) of the fine sand grade. Generally, medium sand is more abundant than very fine sand in the muddy sands prior to the sandy mud interval, with very fine sand becoming increasingly more abundant than medium sand after then. This shows a gradual decrease in sand grain size since the appearance of sandy mud in the early 1970's, coinciding with the progressive increase in sand content of the sediment since that time.

11.4.2.3. Sand characteristics

Lithic sand content is quite high compared to other cores, ranging from 40 to 65%, typical of river sands in the modern estuarine environment. Lithic content increased slightly with depth following the increase in sand grain size, being 55 to 65% within the first muddy sand section, but 40 to 55% within the overlying sandy mud and muddy sand.

The sand fraction is moderately to moderately well sorted, and sand roundness is very angular to angular, typical of riverine sands in the modern area.

11.4.2.4. Shell content

The core can be divided into four zones according to shell content. The earliest zone (127.5 – 98cm) consists of very slightly shelly muddy sand. This zone contains occasional clam shells (mainly of *Notospisula trigonella*) which are only of isolated occurrence. The following zone (98 – 74.5 cm) contains moderately shelly (clam) muddy sand. This is the shelliest section of the core, yet shell content is considerably less than in the much of the Duckhole core, being equivalent to the thin (5cm thick) moderately shelly layer in that core. This layer had a gradational base, yet a fairly sharp upper boundary. A third zone between 74.5 and 53.5 cm depth (? until late 1960's) is represented by slightly shelly (clam) muddy sand. Within this zone, clam shell content is minor, though indicative of a layered arrangement. Above this zone (late 1960's until 2002), clam shells are rare, and sediment consists of sandy mud or muddy sand.

11.4.2.5. Plant material

Sediments within the core contain the remains of plant material, consisting of woody and seagrass remains, similar to that found within the Duckhole Rivulet core. Plant material

was rare within the initial muddy sand section of the core, abundant within the sandy mud interval, and common within the second muddy sand section.

The sudden increase in plant material during the early 1970's, is probably indicative of the increased delivery of terrestrial plant matter by fluvial flow which accompanied the sudden increase in mud being delivered. It may also indicate that the greater nutrients supplied by muddier sediments promoted aquatic plant growth in the area. The increase in mud content also coincides (as similarly observed in the Duckhole Rivulet core) with the disappearance of shells within sediments.

11.4.2.6. Depositional environments

From the base of the core (age unknown) until the late 1960's, sediment consisted of muddy sand, with fairly consistent mud content. A gradual increase in clam shell content occurred upcore within the muddy sand unit, peaking at 74.5 – 98 cm depth, subsequently decreasing until absent in the late 1960's. This unit indicates that for some period of time prior to the late 1960's, mud deposition was relatively low and stable, within the Coal River near Samphire Island.

The appearance and disappearance of clam shells within the unit is probably indicative of changing pH conditions, as similarly suggested for clam shell content in the Duckhole Rivulet core. In the latter core, an increase in the delivery of nutrients was suggested as leading to a progressive lowering of dissolved oxygen concentrations, causing a reduction in bottom water pH, and consequently, a progressive loss of clam shell content in the core. Within the Samphire Island core there is evidence of calcite dissolution upon clam shells to support this theory. However, the timing of the presence of the clam shell layer in the Samphire Island core differs from that in the Duckhole Rivulet core, coinciding instead with the oyster layer of that core. The end of the oyster layer is likely to have been a result mainly of increasing water turbidity and sedimentation, but there is evidence of decreasing pH upcore within the layer, which would possibly have been sufficient to account for the loss of clam shells within the Samphire Island core by the late 1960's. The significantly higher sedimentation rate within the Samphire Island core, compared to the Duckhole Rivulet core, may explain why clam shell layers are less dense than in the other core, as such would make shell content more diluted within the sediment.

It is uncertain what caused the appearance of the clam shell layer after an earlier period of low shell content within sediments, although it suggests an earlier period of low pH conditions.

During late 1960's, the delivery and accumulation of mud within the Coal River increased dramatically, leading to the appearance of sandy muds near Samphire Island. The near-absence of clam shells within the sandy mud, suggests that very low pH conditions, due to the high nutrient content of the mud, inhibited clam growth and survival such that numbers were very low. However, an increase in sedimentation rate, and water turbidity, may have also been a contributing factor.

Mud content decreased substantially from the early 1970's until the early 1980's, indicating that the delivery and accumulation of mud decreased almost as quickly as it had risen. From the early 1980's until 2002, mud delivery and accumulation decreased gradually, although this decrease appears to have been greater after the mid-1990's. Currently, mud content is only slightly higher than it was before the late 1960's.

11.4.3. Fossil foraminiferal distribution and facies

11.4.3.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is quite low (lower than in the Duckhole Rivulet core), with Fisher α indices ranging from 0.34 to 1.67, averaging 0.97. From the base of the core to the top of the moderately shelly layer, diversity gradually increases, peaking at the top (Figure 11.10). Just above the relatively sharp boundary with the overlying slightly shelly layer, diversity drops substantially, possibly in response to the drop in pH indicated by declining shell content. However, within the slightly shelly layer, diversity increases upcore again, peaking within the base of the sandy mud unit. Within the top half of the sandy mud unit, diversity again drops suddenly before rising again within the overlying muddy sand unit, within which it has again continued to decline.

(ii) Abundance

Foraminiferal abundance is low (considerably lower than in the Duckhole Rivulet core), ranging from 1.4 to 11 specimens per gram of sediment, and averaging only 6.4. Abundance is lowest at the base of the core, rising upcore to reach a maximum within the base of the moderately shelly layer (Figure 11.10). Abundance drops significantly at the top of this shelly layer, and has remained consistent (at 4 – 7 gm/sediment) until 2002.

The greater abundance of foraminifera within the base of the moderately shelly layer suggests either that conditions were more favourable for population growth, or that a

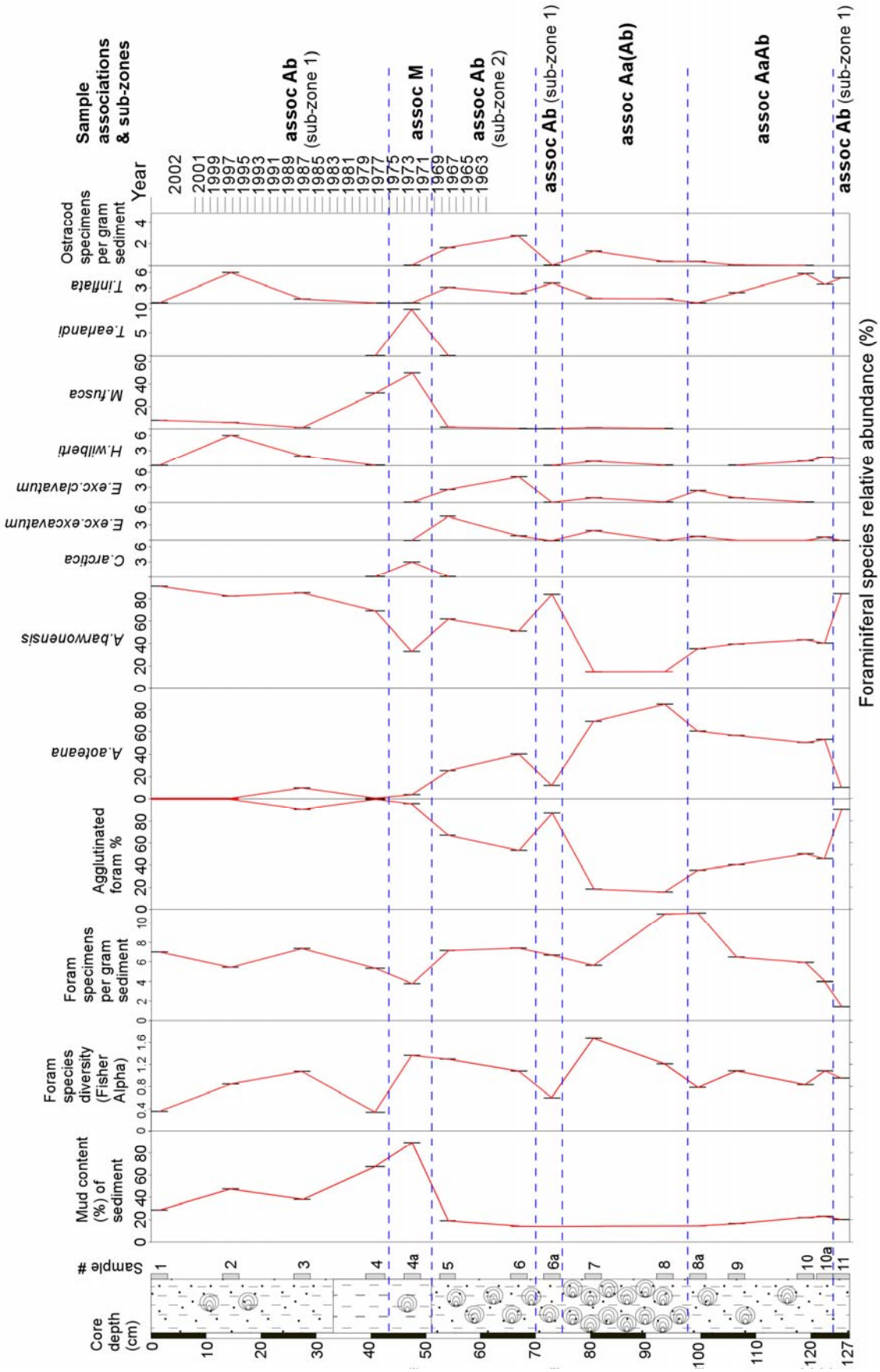

Figure 11.10. Fossil foraminiferal distribution in the Samphire Island core.

greater accumulation of foraminiferal tests was possible due to the concentration of shells caused by low sedimentation rate.

(ii) Agglutinated Foraminifera

The abundance of agglutinated foraminifera ranges from 16 to 100% within the core, increasing upcore overall. From the base of the core to the base of the moderately shelly layer, agglutinated content decreases, remaining at its lowest within the shell layer. Such is indicative of a transition from intermediate to high pH conditions, which allowed increasing numbers of clams and calcareous foraminifera to inhabit the area. This theory is supported by evidence of an increasing degree of calcareous test dissolution towards the base.

Across the transition from the underlying moderately shelly layer to the overlying slightly shelly layer, agglutinated content increases markedly from 18 to 88%. This sudden change is indicative of a drop from high to low water pH, which also caused the sudden drop in clam shell content. Immediately above the base of the slightly shelly layer, agglutinated content decreases to 53% (indicative of intermediate pH), before gradually increasing again upcore within the layer.

With the appearance of the sandy mud layer (late 1960's to early 1970's), agglutinated content increased dramatically to 96%, remaining very high (90 – 100%) until 2002. This indicates that the low pH conditions which occur in the bottom waters of the Coal River adjacent to Samphire Island were achieved by the late 1960's to early 1970's, and have remained consistently low since then.

The varying bottom water pH indicated by the core sediments, is likely to have been due to varying dissolved oxygen levels, related to either water stagnation, or levels of nutrients. To as lesser extent, it may relate to varying salinity, as more agglutinated species tend to prefer lower salinity conditions within the estuary.

11.4.3.2. Sample associations and sub-zones

A combined cluster analysis of all Samphire Island core sub-samples and modern surficial samples identified the new foraminiferal sample associations AaAb and Aa(Ab) within the lower third of the core; association M between the late 1960's and mid-1970's; and association Ab within the slightly shelly layer (from ? until the late 1960's), between the mid-1970's and 2002, and within the basal 3 cm of the core (Figure 11.10). The occurrence of association Ab within the basal 3 cm of the core is unusual, and may be a consequence

of coring sampling technique as it is inconsistent with species data of the sub-sample immediately above it. Association Ab could be further divided into sub-zones 1 and 2.

As in the Duckhole Rivulet core, it is mainly the opposing abundance of *Ammonia aoteana* (decreasing overall upcore) and *Ammobaculites barwonensis* (increasing overall upcore) which provides the major trend in species composition, forms its subdivision into associations. However, the abundance of *M. fucsa* is important in distinguishing association M.

(i) Association AaAb

Association AaAb represents the lower 25 cm of the core (age unknown). This association was also found in the Duckhole Rivulet core, where it occupied shelly sediments dating from the early 1920's to late 1980's. The association within the Samphire Island core was grouped by cluster analysis with subzone 1 of the association in the Duckhole Rivulet core, which occupied the oyster layer (early 1920's to mid-1970's).

In the core, the association is co-dominated by *A. aoteana* (average abundance of 55%) and *A. barwonensis* (40%), with minor *T. inflata* (3%), *E. excavatum clavatum* (0.9%), *H. wilberti* (0.7%), and *E. excavatum excavatum* (0.4%).

Specimen abundance averages 6.9 specimens/gm sediment and decreases upcore; whereas, species diversity is considerably lower than the association within the Duckhole Rivulet core, averaging 0.95. Mud content decreases slightly upcore from 24% at the bottom to 14% at the top.

The association is a mixed agglutinated-calcareous assemblage, mainly composed of *A. barwonensis* and *A. aoteana*, with few other species. The abundance of these two species is fairly consistent, although *A. barwonensis* become slightly more abundant upcore, with *A. aoteana* decreasing slightly.

As described in the Duckhole Rivulet core, the association represents a shallow subtidal environment of the upper estuary where pH was once significantly higher than it is today. The 'mixed agglutinated and calcareous' assemblage (with calcareous foraminifera more abundant) implies intermediate-high pH conditions, yet the species composition is indicative of similar salinity and water depth to that in which the core was obtained.

(ii) Association Aa(Ab)

General characteristics and faunal composition of the new association

Before describing the occurrence of association Aa(Ab) within the core, the general characteristics and species composition of this new foraminiferal sample association will be described. Table 11.5 summarises this information based upon the occurrence of the association in sub-samples of the Samphire Island and Stinking Point cores. As with association AaAb, association Aa(Ab) no longer exists within the modern estuarine environment, but the species it contains are still present. Association scores for species of the association are summarised in Appendix G.

Mud content (%)	**Abundance** (specimens/gm sediment)	**Species diversity** (Fisher α)	**Agglutinated content** (%)	**Cores present in**
14 *(8 - 19)*	7 *(3 - 11)*	Low 1.1 *(0.8 – 1.7)*	9 *(0.9 - 18)* implied pH = high	Samphire Is. Stinking Pt.
Species		**Relative abundance** (%)	**Species**	**Relative abundance** (%)
Ammonia aoteana		89 *(79 - 97)*	*Trochammina inflata*	0.6 *(0 – 1)*
Ammobaculites barwonensis		8 *(0 - 16)*	*Miliammina fusca*	0.2 *(0 – 0.97)*
E. excavatum clavatum		1.4 *(0 – 2.7)*	*Haplophragmoides wilberti*	0.16 *(0 – 0.97)*
E. excavatum excavatum		1.2 *(0 – 2.8)*		

Table 11.5. Foraminiferal composition of the extant sample association Aa(Ab).

The association has low abundance and low species diversity, typical of the shallow subtidal areas of the upper estuary. It is dominated by calcareous foraminifera, implying high pH conditions which are no longer found in the upper estuary.

The association is dominated by *A. aoteana* (average abundance of 89%) with sub-dominant *A. barwonensis* (8%). *E. excavatum clavatum, E. excavatum excavatum, T. inflata, M. fucsa*, and *H. wilberti* are minor species. The association contains similar species to association AaAb, except that it contains less species, and is dominated by *A. aoteana*, rather than co-dominated by *A. aoteana* and *A. barwonensis*. These species are euryhaline, yet prefer similar brackish to very slightly brackish salinity, indicating that the association is indicative of conditions similar to that implied by association AaAb, except that pH is high rather than intermediate-high.

Presence of the association within the Samphire Island core

Association Aa(Ab) is found between depths of 98 – 74.5 cm, contained within the moderately shelly (clam), muddy sand layer (age range unknown). Within the core, the

association is dominated by *A. aoteana* (average abundance of (81%) sub-dominant *A. barwonensis* (15%) with minor *E. excavatum excavatum* (1.0%), *T. inflata* (0.9%), *M. fucsa* (0.5%), *E. excavatum clavatum* (0.5%), and *H. wilberti* (0.5%). Specimen abundance ranges from 6 to 11 specimens/gm sediment, averaging 8. Species diversity is low, with the Fisher α Index averaging 1.4. Species composition remains consistent between sub-samples.

(iii) Association Ab

Association Ab represents the upper half of the core from 74.5 cm depth (age unknown) to the late 1960's, and from the mid-1970's until 2002. The association is dominated by *A. barwonensis* (average abundance of 75%). Secondary species are *A. aoteana* (13%) and *M. fucsa* (7%), and minor species include *T. inflata* (2.3%), *H. wilberti* (1.1%), *E. excavatum clavatum* (1%) and *E. excavatum excavatum* (0.8%). Specimen abundance ranges from 5.3 to 7.3 specimens/gm sediment, averaging 6.6. Species diversity is low, with the Fisher α Index averaging 0.8.

The abundance of agglutinated foraminifera increases upcore within the association suggesting that pH levels decreased with time. The main changes in species abundance are an overall increase in abundance of *A. barwonensis*, and a decrease in *A. aoteana*. *E. excavatum excavatum* and *E. excavatum clavatum* are present only in the earlier section of association Ab, absent from the core after the late 1960's, and only of very minor abundance earlier in the core. This is likely to be a result of the lowering pH conditions, as these species were noted similarly in the Duckhole Rivulet core to appear once the abundance of *A. aoteana* had dropped substantially following a significant drop in water pH. After the late 1960's, *E. excavatum excavatum* and *E. excavatum clavatum* are absent (and *A. aoteana* very minor or absent) because water pH had reached low enough levels to cause severe calcite dissolution.

Two sub-zones were identified within the association by cluster analysis. Sub-zone 1 occupies the core within two sections: a short interval within the slightly shelly muddy sand just above the moderately shelly layer (74.5 – 70cm depth), and within sediments after the mid-1970's. It contains a greater abundance of agglutinated foraminifera (average 95%) than sub-zone 2 and is dominated by *A. barwonensis* (average abundance of 83%) and very low abundance of *A. aoteana* (average 5%). The pH conditions of this sub-zone were low.

Sub-zone 2 occupies the slightly shelly sediments of the core at core depths 70 – 51 cm (unknown age to late 1960's). Although still containing a high abundance of *A. barwonensis*, agglutinated foraminifera content is substantially lower than in sub-zone, averaging 60%, and *A. aoteana* has an average abundance of 33%. Additionally, the calcareous species, *E. excavatum excavatum* and *E. excavatum clavatum* are present, unlike in sub-zone 1. This indicates that pH conditions in sub-zone 2 were low-intermediate.

(iv) Association M

Association M is represented by one sub-sample in the core, occupying sediments dated from late 1960's to the mid-1970's. The association is dominated by *M. fucsa* (abundance of 49%), with sub-dominant *A. barwonensis* (33%). Secondary species include *T. earlandi* (10%), *C. arctica* (3%), and *A. aoteana* (3%). Specimen abundance is 3.8 specimens/gm sediment, and species diversity is low, with the Fisher α Index of 1.4. Agglutinated foraminifera content is very high (96%), indicating that pH conditions were low.

The association within the core coincides with the appearance of the sandy mud, when mud content is greatest. As pH conditions indicated by the underlying subzone 2 of association Ab have been indicated as low-intermediate, the appearance of association M is indicative of a drop in pH to low levels. As association Ab is generally indicative of low pH conditions, association M is likely to be present within the core as a result of the dramatic increase in mud deposition at the locality at the end of the 1960's. In the Midway Bay core, the transition from association Ab to C with decreasing core depth, was related mainly to increased nutrient supply over time increasing the foraminiferal abundance of certain species, with *C. arctica, M. fucsa* and *T. earlandi* able to increase in abundance substantially more than *A. barwonensis*. This may also have occurred within the Samphire Island core when the mud content of sediments increased substantially. The greater nutrient supply to these muddy sediments would have promoted increased abundance of *M. fucsa, C. arctica* and *T. earlandi* over *A. barwonensis*, such that association M became present. Thus, association M appeared as a result of increased nutrient supply in the muddy sediment. The abundance of *M. fucsa* is still significant within the upper half of the sandy mud layer, immediately above association M (being contained in association Ab), indicating the relationship the species has with mud content.

11.4.3.3. Foraminiferal palaeoenvironments - conditions and changes

The foraminiferal fauna of Samphire Island core appears to vary mainly with changes in pH, and to a lesser extent, changing levels of nutrient supply (correlating with mud content). Changes in pH are probably related to variations in supply of dissolved organic matter in fluvial waters delivered to the area (as observed in the modern estuarine environment), but may also be related, in some degree, to water stagnation.

Salinity and water depth do not appear to have changed significantly, although, agglutinated foraminifera content can also be indicative of salinity to some extent. The low species diversity and abundance of specimens found throughout the core is also typical of the shallow water foraminiferal fauna of the modern environment where the core was obtained.

The foraminiferal fauna of the basal 25 cm of the core belongs to association AaAb (which is no longer present in the estuary), and is indicative of a palaeoenvironment of intermediate-high pH conditions. The pH conditions caused a mixed agglutinated-calcareous foraminiferal fauna to be present, and prevented significant clam shell growth and survival.

From 98 – 74.5 cm, moderately shelly (clam) sediments contain a dominantly calcareous foraminiferal fauna belonging to association Aa(Ab) (also no longer present in the estuary). The low agglutinated foraminiferal content and presence of abundant clam shells is indicative of high pH conditions.

From 74.5 – 70 cm, agglutinated foraminiferal content increases dramatically, indicating a significant drop in pH to low levels. The fauna in this section of the core is dominated by *A. barwonensis*, belonging to association Ab (sub-zone 1), which is currently abundant in shallow subtidal depths of the estuary where pH is low.

From 70 – 53.5 cm (age unknown to late 1960's), association Ab is still present, but as sub-zone 2. This sub-zone is characterised by an increase abundance of calcareous foraminifera (particularly *E. excavatum excavatum* and *E. excavatum clavatum*) relative to sub-zone 1, and is indicative of an increase in pH to low-intermediate.

From the late 1960's until the mid-1970's, the foraminiferal fauna changed dramatically as a large increase in the mud content of sediment provided more nutrients, promoting an increase in abundance of *M. fucsa*, *T. earlandi* and *C. arctica*, such that association M (indicative of low pH) became established. A subsequent decline in mud content after the mid-1970's (until 2002), lead to the return of association Ab (sub-zone 1), with pH

conditions remaining permanently low, such that calcareous foraminifera were absent or rare.

11.4.4. Fossil ostracod distribution and facies

11.4.4.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is low, with Fisher α indices ranging from 0.9 to 1.6, averaging 1.2.

(ii) Abundance

Ostracod abundance is very low ranging from 0 to 2.3 specimens per gram of sediment. Ostracods are present in only six sub-samples, with three containing only a few specimens (Figure 11.11). Ostracods were found only in sub-samples within which clam shells were also present, and are totally absent within sediments after the late 1960's.

The absence of ostracods from much of the core, and low abundance when present, is further indication of generally lower pH conditions within the Samphire Island core compared to those of the Duckhole Rivulet core.

11.4.4.2. Sample associations and sub-zones

Cluster analysis of three Samphire Island core sub-samples identified associations LhPs and Mh within the core. Association Mh was present at 87 – 61 cm depth (age unknown), and association LhPs was present at 61 – 53.5 cm depth (early to late 1960's) (Figure 11.11). Elsewhere in the core, ostracods were either too low in number to permit accurate cluster analysis, or were totally absent.

(i) Association Mh

The association is dominated by *M. hornibrooki* (average abundance 64%), with secondary *L. hartmanni* (24%), and minor *P. subaustralis* (5.7%), *O. baragwanathi* (4.6%), *C. puri* (0.8%), *A. vandenboldi* (0.8%), and *P. portphillipensis* (0.8%). The association is present within moderately to slightly shelly sediments (87 – 61 cm depth). Within the modern estuary, the association is typical of intertidal depths, and the presence of *L. hartmanni*, *P. subaustralis*, and *O. baragwanthi* within the association in the core is

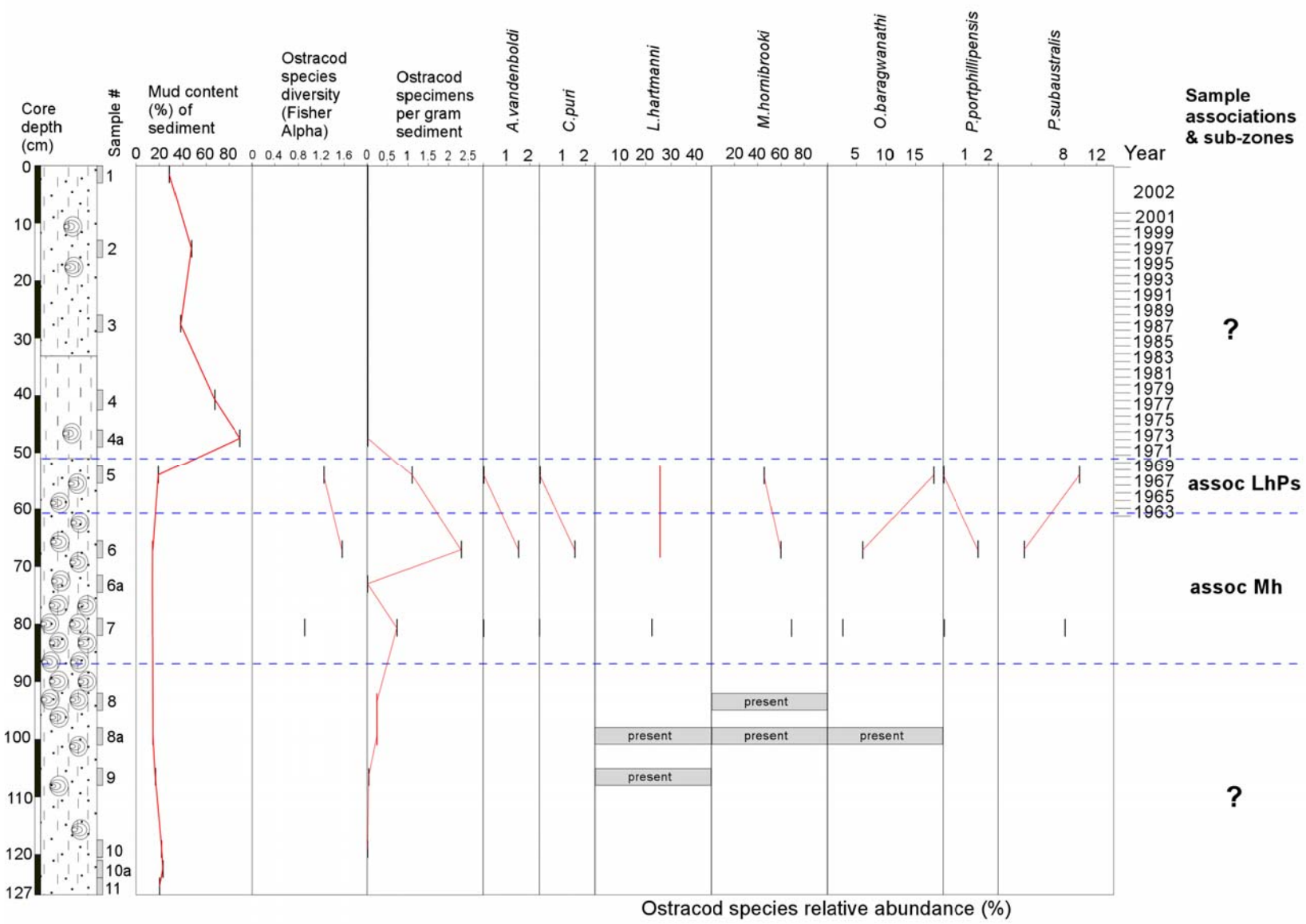

Figure 11.10. Fossil ostracod distribution in the Samphire Island core.

indicative of such depths under freshwater influence, as in the Coal River. However, although cluster analysis identified association Mh within the core, the species composition is, due to the abundance of *L. hartmanni*, actually intermediate between that typical of Mh and that of LhPs (which directly overlies it).

The absence of the ostracods in the core prior to the appearance of this association, is indicative of more favourable conditions at core depths 87 – 61 cm, than previously. It is likely that this correlates with an increase in pH levels, as suggested by foraminifera and clam shell content. The change in species composition upcore within the association (increase in abundance of *O. baragwanthi, L. hartmanni*, and decrease in *M. hornibrooki*) is indicative of decreasing water salinity and/or declining pH (and possibly also increasing water turbidity). As discussed in the ostracods of the Duckhole Rivulet core, the increase in abundance of species typical of lower salinity may actually be indicative of declining pH, as lower pH conditions tend to occur in lower salinity areas of the modern estuary. As an increase occurs in the agglutinated foraminifera content of sediments from 87 to 61 cm depth, as well as a decrease in clam shell content, it is more likely that declining pH is the cause of upcore changes in species abundance within the association. This is also supported by evidence of greater calcite dissolution upon shells at decreasing depth within the association.

(ii) Association LhPs

The association is dominated by *M. hornibrooki* (abundance 46%) with sub-dominant *L. hartmanni* (abundance 26%). Secondary species include *O. baragwanathi* (18%) and *P. subaustralis* (10%). The association is present in one sub-sample, and is implied to cover sediments from the early to late 1960's. The species composition of the association is quite different from its occurrence in the modern environment, with *M. hornibrooki* typically much less abundant. The upcore changes in species abundance within the underlying association Mh continue into association LhPs, with *O. baragwanathi* and *P. subaustralis* becoming much more abundant. These two species are indicators of freshwater influence within the modern estuary, and are therefore suggestive of a drop in salinity or of the lower water pH typical of such areas. Evidence of calcite dissolution upon ostracod tests supports declining pH as the major cause of the transition from association Mh to LhPs. The trend may also be indicative of increasing water turbidity as, in the modern estuary, *M. hornibrooki* is less tolerant of reduced illumination than *O. baragwanathi* and *P. subaustralis*.

11.4.4.3. Ostracod palaeoenvironments – conditions and changes

Ostracods have been absent from the very shallow subtidal waters of the Coal River adjacent to Samphire Island since the late 1960's, as well as in sediments of the location (of unknown age) below 110 cm core depth. Ostracods only reached appreciable numbers in the area when moderately or slightly shelly muddy sands were present, and their absence elsewhere in the core is probably a result of low pH conditions. Ostracods in the modern estuary are more sensitive to lower pH conditions than foraminifera, and it is this sensitivity which has prevented their population growth within the area.

Ostracod associations are present within two sections of the core. The first, association Mh (core depth 87 to 61 cm – unknown age), indicates very shallow waters under freshwater influence, similar to the modern environment. The second, association LhPs, was present from the early to late 1960's (replacing association Mh), and is indicative of either greater freshwater influence or lower pH levels than for the underlying association. However, it is likely that pH changes were mainly responsible for this transition, as clam shell content and agglutinated foraminifera content suggest. These changes in pH are either a consequence of increasing organic matter content in waters being supplied to the area, or of increasing water stagnation.

After the late 1960's, ostracods disappeared from the area, when mud content in sediments increased dramatically, leading to a further reduction in pH, below the tolerance levels of ostracods.

11.4.5. Seafloor environments – changes and links to historical activities

11.4.5.1. Before the late 1960's – changes in agricultural activity?

Prior to the late 1960's, mud content within sediments in the very shallow subtidal waters of the Coal River, adjacent to Samphire Island, was low and did not vary significantly. However, there were significant changes in the benthic fauna, which appear to indicate changes in water pH, with pH increasing and then decreasing. It is not known when these changes in pH occurred. However, as the Duckhole Rivulet core displayed evidence of the impact of agricultural activity upon the seafloor environment back to the early 1920's, and considering forest clearing in the estuary catchment first occurred in the early 1800's, it is likely that changes in land use are responsible for those changes in benthic fauna within the Duckhole Rivulet core prior to the late 1960's.

Changes in pH within the modern estuarine environment have been linked either to nutrients (dissolved in water, or particulate in sediments) or water stagnation, both of

which can lead to a reduction in dissolved oxygen levels, and hence, pH in the bottom water. It is most likely that varying intensity of fertiliser usage before the late 1960's has caused the changes in water pH, by variations in the supply of dissolved organic matter in fluvial waters (as observed in the modern estuarine environment); however, changed water stagnation (perhaps by weir construction) cannot be ruled out from also causing pH changes. The lack of change in mud content of sediments suggests that water turbidity and mud delivery have not increased significantly, and did not cause any change in water pH.

The basal 25 cm of the core contains very small amounts of clam shells, no ostracods, and contains mixed agglutinated-calcareous foraminifera assemblage indicative of a palaeoenvironment of intermediate-high pH conditions. From 98 – 74.5 cm, an increase in water pH to high levels, allowed moderate clam shell content in the sediments, as well as increased abundance of ostracods and more calcareous foraminiferal content. From 74.5 – 70 cm, a significant drop in pH to low levels occurred, such that clam shell and ostracod content dropped significantly, and agglutinated foraminifera became more abundant. From 70 – 53.5 cm (age unknown to late 1960's), an increase in pH to low-intermediate levels, allowed an increase in ostracod and calcareous foraminifera abundance, yet clam shells remained of low abundance in sediments.

The series of changes in pH which have occurred in sediments prior to the late 1960's, suggests that increased fertiliser usage has been responsible for the progressive loss of clam shells, ostracods and calcareous foraminifera within the area prior to the late 1960's. This drop from high to low pH levels was drastic initially, but rising to low-intermediate levels, and then finally dropping to low levels again in the late 1960's.

Sediments between the core base and the clam shell layer suggest an earlier period of low-intermediate pH conditions. The cause of this earlier period of reduced pH is unclear, as the lack of age data means that one cannot be certain if it occurred before or after the onset of European settlement, such that an anthropogenic or natural cause cannot be confirmed.

11.4.5.2. After the late 1960's – increased agricultural activity

Increased agricultural activity in the late 1960's appears to have caused a dramatic increase in mud content in the sediments of the Coal River. This is probably a result of more topsoil exposure, leading to increased sediment content in runoff delivered to the river and stream inputs to the upper estuary. This is supported by the increase in terrestrial

plant matter within sediments. However, the clearance of large areas within the catchment by the bushfires of 1967 is likely to have been a contributing factor.

The increase in mud content in sediment provided increased nutrient supply for particular species of foraminifera, leading to a change in species composition, as well as increased aquatic plant growth. It also lead to a further decrease in pH, which eliminated the presence of ostracods and clams.

From the late 1960's until the mid-1980's, the amount of mud accumulating on the seafloor of the Coal River gradually decreased. This lead to a further change in foraminiferal species composition, reflecting low pH conditions which have continued until 2002.

Since the mid-1980's, mud content has decreased gradually, although a minor rise during the early to mid-1990s could be attributable to construction of the Craigbourne Dam (increasing water stagnation, leading to more mud settling) and the South-east Irrigation Scheme (increasing cropping practices in the catchment, leading to increased soil runoff).

11.5. Stinking Point core

11.5.1. Introduction

This core was obtained from 0.5 m water depth within the mouth of the Coal River, adjacent to Stinking Point (Figure 10.1). Ten sub-samples were taken from the core and subjected to sediment, foraminiferal and ostracode analysis (Appendices F, G). Excess ^{210}Pb activity was near background levels within sediments of the core, making dating of the core impossible by the technique.

11.5.2. Lithostratigraphy

The core is 81.5 cm long, consisting of grey muddy sand, which is increasingly shell-bearing with depth.

11.5.2.1. Particle-size distribution

The muddy sands of the core have a consistently low mud (8 - 18%, averaging 15%). Sand is generally of fine to medium grade. Above 20 cm depth, sand becomes finer with decreasing core depth (Figure 11.12). The granule/pebble fraction is more abundant with increasing core depth, due to the increasing shell content.

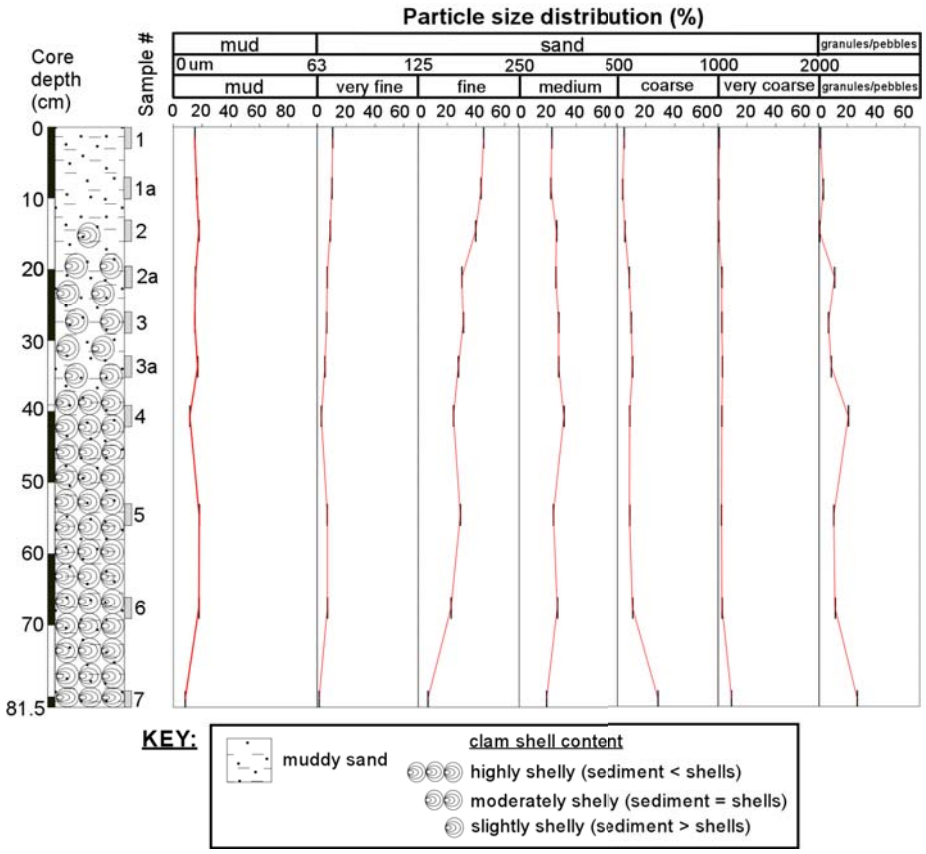

Figure 11.12. Stinking Point - particle-size distribution data.

11.5.2.2. Sand characteristics

Lithic sand content is quite high (40 - 70%), typical of river sands in the modern estuarine environment. As in the Samphire Island core, lithic content increases slightly with depth following the increase in sand grain size, 55 to 70% below 20 cm depth, but 40 to 55% above it.

The sand fraction is moderately to moderately well sorted, and sand roundness is very angular to angular, typical of riverine sands in the modern area.

11.5.2.3. Shell content

The core can be divided into four zones according to shell content. The first zone (81.5 – 37 cm) consists of highly shelly muddy sand. Within this zone, clam shells (mainly of *Notospisula trigonella*), and to a lesser degree gastropods, are very abundant, making a dense shell layer. The second zone (37 – 17.5 cm) contains moderately shelly (clam) muddy sand, within which shell content is relatively high, yet less so than in the underlying

sediments. Within this zone, shell content increases with greater core depth. A third zone (17.5 – 13 cm) is represented by slightly shelly (clam) muddy sand. Within this zone, clam shell content is minor, and occurs in layers. Above this zone (13 – 0 cm) clam shells are absent.

11.4.2.4. Plant material

As in the Duckhole Rivulet and Samphire Island cores, sediments of the Stinking Point core contain the remains of plant (woody and seagrass) material. Plant material is rare within the moderately and highly shelly muddy sands, yet present within the overlying slightly shelly and non-shell bearing muddy sands.

The abrupt increase in plant material above the shellier layers is likely to indicate (as in the other cores) the increased delivery of terrestrial plant matter by fluvial flow, as well as greater nutrients by such waters promoting aquatic plant growth in the area.

11.4.2.5. Depositional environments

As in the Duckhole Rivulet core, there has been an overall decrease in the shell content of muddy sands within the mouth of the Coal River, off Stinking Point, in recent history. This change in shell content is characterised by the decrease in clam shell content within sediments with decreasing core depth. This decrease occurs in stages, with a basal highly shelly layer (81.5 – 37 cm), a moderately shelly layer (37 – 17.5 cm), a slightly shelly layer (17.5 – 13 cm) and a zone in which shells are absent (13 – 0 cm).

As in the Duckhole Rivulet and Samphire Island cores, a change in water quality is likely to have caused this decrease in the shell content of sediments. The sudden increase in plant material at the top of the moderately shelly layer suggests an increase in delivery of terrestrial plant matter by fluvial flow, as well as greater nutrients of such waters promoting aquatic plant growth. Such would have caused a reduction in dissolved oxygen levels, and therefore, a lowering of pH levels. An increase in nutrient content of sediments could also have contributed to lowering bottom water pH.

The reduction in pH is likely to have been the main cause in reducing shell content of the sediments at shallowing depth within the core (as suggested by the other cores); and such is indicated by evidence of calcite dissolution upon clam shells being more severe further upcore. However, an increase in sedimentation rate, and perhaps water turbidity, may also have accompanied such pH changes.

11.5.3. Fossil foraminiferal distribution and facies

11.5.3.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is low (with Fisher α indices of 0.8 - 2.06, averaging 1.3) and increases steadily upcore, peaking at approximately 10cm depth (Figure 11.13).

(ii) Abundance

Foraminiferal abundance is low (1.5 - 10 specimens per gram of sediment, averaging 4.2). Abundance is significantly greater within the highly shelly layer than in overlying sediments (as seen in the other cores), suggesting either that conditions were more favourable for population growth, or that a greater accumulation of foraminiferal tests was possible due to the concentration of shells caused by low sedimentation rate.

(iii) Agglutinated Foraminifera

The abundance of agglutinated foraminifera increases overall upcore. Agglutinated foraminifera content is consistent within the different shelly layers, being very low (average of 4.6%) within the highly shelly layer, moderate (30%) within the moderately shelly layer, and significantly greater within the slightly shelly layer (83%). Above the slightly shelly layer, agglutinated foraminifera content drops significantly to 35%, before rising to be 55% at the top of the core.

As explained in the discussion of the other cores, variation in agglutinated content is a consequence mainly of changing bottom water pH levels, but may to some degree, be indicative of varying freshwater influence. The close correlation between increasing agglutinated foraminifera content, and decreasing shell content, is further evidence that the same cause is behind the changes which occur in both.

Consequently, the agglutinated content of the highly shelly layer is indicative of high pH levels. Within the moderately shelly layer intermediate-high pH levels are indicated; whereas, in the slightly shelly layer, low pH levels (causing severe calcite dissolution) are indicated. Within the overlying shell-free muddy sands, intermediate pH levels occurred, decreasing at shallowing depth, yet remaining, at the top of the core, still above that represented in the slightly shelly layer.

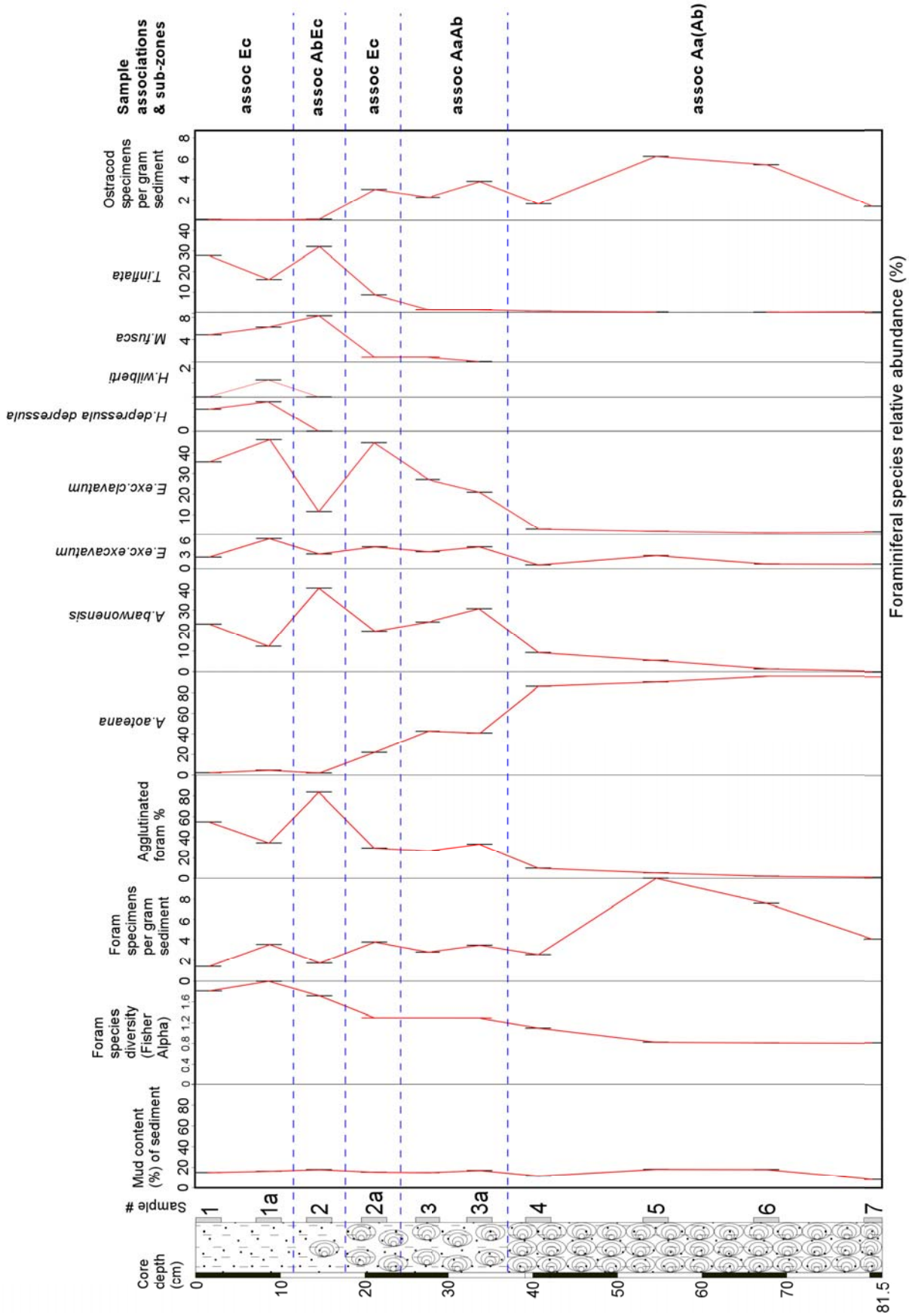

Figure 11.13. Fossil foraminiferal distribution in the Stinking Point core.

11.5.3.2. Sample associations and sub-zones

A combined cluster analysis of all Stinking Point core sub-samples and all modern surficial samples identified, the new foraminiferal sample associations Aa(Ab) and AaAb within the highly shelly and moderately shelly layers, respectively; as well as AbEc within the slightly shelly layer, and Ec within the overlying shell-free muddy sands and within the top 10 cm of the moderately shelly layer (Figure 11.13).

As in the previous cores, it is mainly the opposing abundance of *A. aoteana* (decreasing upcore) and *A. barwonensis* (increasing upcore) which cause the main subdivisions into associations; however, within the upper half of the core, the abundance of *E. excavatum clavatum* and *T. inflata* are just as important.

(i) Association Aa(Ab)

The association has low abundance and low species diversity (with the Fisher α Index averaging 0.9), typical of the shallow subtidal areas of the upper estuary, and is dominated by calcareous foraminifera indicative of high pH conditions no longer found in the upper estuary. Association Aa(Ab) at depths 81.5 – 37 cm, is contained within the highly shelly, muddy sand layer. The association is dominated by *A. aoteana* (average abundance of 92%), with secondary *A. barwonensis* (4%), and minor *E. excavatum clavatum* (1.8%), *E. excavatum excavatum* (1.4%) and *T. inflata* (0.4%). Specimen abundance ranges from 3 - 10 specimens/gm sediment, averaging 6.1. Species composition remains consistent between sub-samples.

Several changes in species composition occur upcore within the association, indicating slightly decreasing pH levels, including: increasing agglutinated foraminifera content; decreasing *A. aoteana*; increasing *A. barwonensis*; and increasing *E. excavatum clavatum* and *E. excavatum excavatum*.

(ii) Association AaAb

As in association Aa(Ab), association AaAb has low abundance and low species diversity (with the Fisher α Index averaging 1.4), typical of the shallow subtidal areas of the upper estuary. However, it has a mixed agglutinated and calcareous foraminiferal assemblage in which calcareous foraminifera are always dominant, thereby indicating intermediate-high pH conditions which, in the upper estuary, currently occur only within the intertidal zone.

Association AaAb at 37 – 17.5 cm, is contained within the moderately shelly, muddy sand layer. It is co-dominated by *A. aoteana* (average abundance of 42%) and *A. barwonesis* (28%), with secondary *E. excavatum clavatum* (24%). Minor species include *E. excavatum excavatum* (4.2%), *T. inflata* (1.9%), *Q. seminula* (0.5%) and *M. fucsa* (0.5%). Specimen abundance ranges from 2.8 to 3.5 specimens/gm sediment, averaging 3.1. Within the association, upcore changes in species composition are indicative of a further, slight decrease in pH levels, with the abundance of agglutinated foraminifera and *A. barwonensis* decreasing, and *E. excavatum clavatum* increasing.

(iii) Association Ec

Association Ec at depths of 24 – 17.5 cm and 13 – 0 cm, is contained within the top of the moderately shelly layer, as well as within the shell-free muddy sands at the top of the core. It is dominated by *E. excavatum clavatum* (average abundance of 42%), with secondary *A. barwonensis* (18%), *T. inflata* (18%), and *A. aoteana* (10%). Minor species include *E. excavatum excavatum* (4.4%), *M. fucsa* (4%), *H. depressula depressula* (3.7%), and *Q. seminula* (0.4%).

The agglutinated foraminifera content averages 40%, thereby indicating intermediate pH conditions. Species composition is different between both sections of the core in which the association occurs, indicating decreasing pH levels upcore. Within the shell-free muddy sands, the abundance of agglutinated foraminifera, *M. fucsa, H. wilberti,* and *T. inflata* is greater, and *A. aoteana* is less. This is further supported by the absence of clam shells and ostracod tests within the shell-free muddy sands.

The agglutinated content of association Ec (average of 40%) is significantly higher than in any sample belonging to the association in the modern estuary (average of 17%). This indicates that the pH conditions of the association at Stinking Point were lower than those in which the association has been identified in the modern environment, being intermediate rather than high. Within the modern estuarine environment, association Ec occurs at intertidal depths, mainly in the Lower Estuary. Calcareous foraminifera dominate due to the water stirring processes imposed by tidal movement and wind-generated wave action, making the water better oxygenated and keeping pH levels raised.

Therefore, the presence of the association at the top of the core obtained from Stinking Point, indicates that the core location is more exposed, and perhaps shallower than that in which the Samphire Island and Duckhole Rivulet cores were obtained. *E. excavatum*

clavatum is the main ecophenotype of *E. excavatum* present (as opposed to *E. excavatum excavatum*) due to its preference for the shallower or more exposed waters.

(iv) Association AbEc

Association AbEc (17.5 – 13 cm) is contained within the top of the slightly shelly layer. The association is dominated by *A. barwonensis* (average abundance of 41%), with sub-dominant *T. inflata* (33%), secondary *E. excavatum clavatum* (12%) and *M. fucsa* (8%). Minor species include *E. excavatum excavatum* (3.2%), *A. aoteana* (2.1%) and *H. wilberti* (1.1%).

The agglutinated foraminifera content is 83%, indicating low pH conditions. This is significantly greater than association AbEc as seen in the modern estuary, within which it ranges from 30 to 70%, averaging 48%. Within the modern estuary, the association occurs in the upper estuary, in intertidal waters which are sheltered, less well-stirred, and therefore, less well oxygenated and with lower pH. The association within the core therefore appears to indicate deeper than intertidal depths, within which agglutinated content could be high. The presence of *E. excavatum clavatum* indicates that the location was still more exposed, and perhaps shallower, than that in which the Samphire Island and Duckhole Rivulet cores were obtained.

11.5.3.3. Foraminiferal palaeoenvironments - conditions and changes

As found in the Duckhole Rivulet and Samphire Island cores, the foraminiferal fauna of the Stinking Point core appear to vary mainly according to changes in pH, with these changes related to variations in supply of dissolved organic matter in fluvial waters, but possibly also related, in some degree, to water stagnation. The response of the foraminiferal fauna to the decreasing pH which occurs overall within the core, is mainly reflected by increasing agglutinated foraminifera content; however (as seen in the other cores), as pH lowers, the abundance of *E. excavatum* ecophenotypes, relative to *A. aoteana*, also increases. As the fauna of the core appear to be indicative of a location more exposed, or shallower, than that of the Duckhole Rivulet and Samphire Island cores, *E. excavatum clavatum* is the dominant ecophenotype present at the top of the core.

The foraminiferal fauna of the basal 41 cm of the core belongs to association Aa(Ab), which indicates a palaeoenvironment of high pH conditions, allowing a dominantly calcareous foraminiferal fauna to be present, and allowing a dense clam shell layer to form.

From 37 – 17.5 cm, moderately shelly (clam) sediments contains a mixed calcareous-agglutinated foraminiferal assemblage in which calcareous foraminifera dominated (association AaAb). This association is indicative of intermediate-high pH conditions (as observed in the Samphire Island core).

From 24 – 17.5 cm, association Ec was present within the top of the moderately shelly layer. This association is indicative of intermediate pH conditions, and is further evidence of the overall decrease in pH levels which occurs upcore. Above this level, association Ab was present (17.5 – 13 cm) within the slightly shelly layer, and the high agglutinated foraminifera content indicates a considerable drop in pH to low levels. In the overlying shell-free muddy sands (13 – 0 cm), association Ec again is present, as pH levels rose again to intermediate levels, which currently occur at the core location (as at the top of the Duckhole Rivulet core).

11.5.4. Fossil ostracod distribution and facies

11.5.4.1. Trends in general characteristics

(i) Diversity

Species diversity within the core is low (with Fisher α indices ranging from 0.8 to 2.7, averaging 1.5), and decreased overall upcore, being greatest within the highly shelly layer (Figure 11.14).

(ii) Abundance

Ostracod abundance is very low ranging from 0 to 7 specimens per gram. Ostracods are present in nine of the ten sub-samples, with three containing only a few specimens. As seen in the other shallow water cores, ostracod abundance correlates with clam shell content, being greatest within the highly and moderately shelly layers (and greatest in the former) (Figure 11.14). Within the slightly shelly layer, ostracods are rare, and more or less absent from the overlying shell-free muddy sands. The absence of ostracods from the latter sediments is further indication of an upcore decline in pH levels.

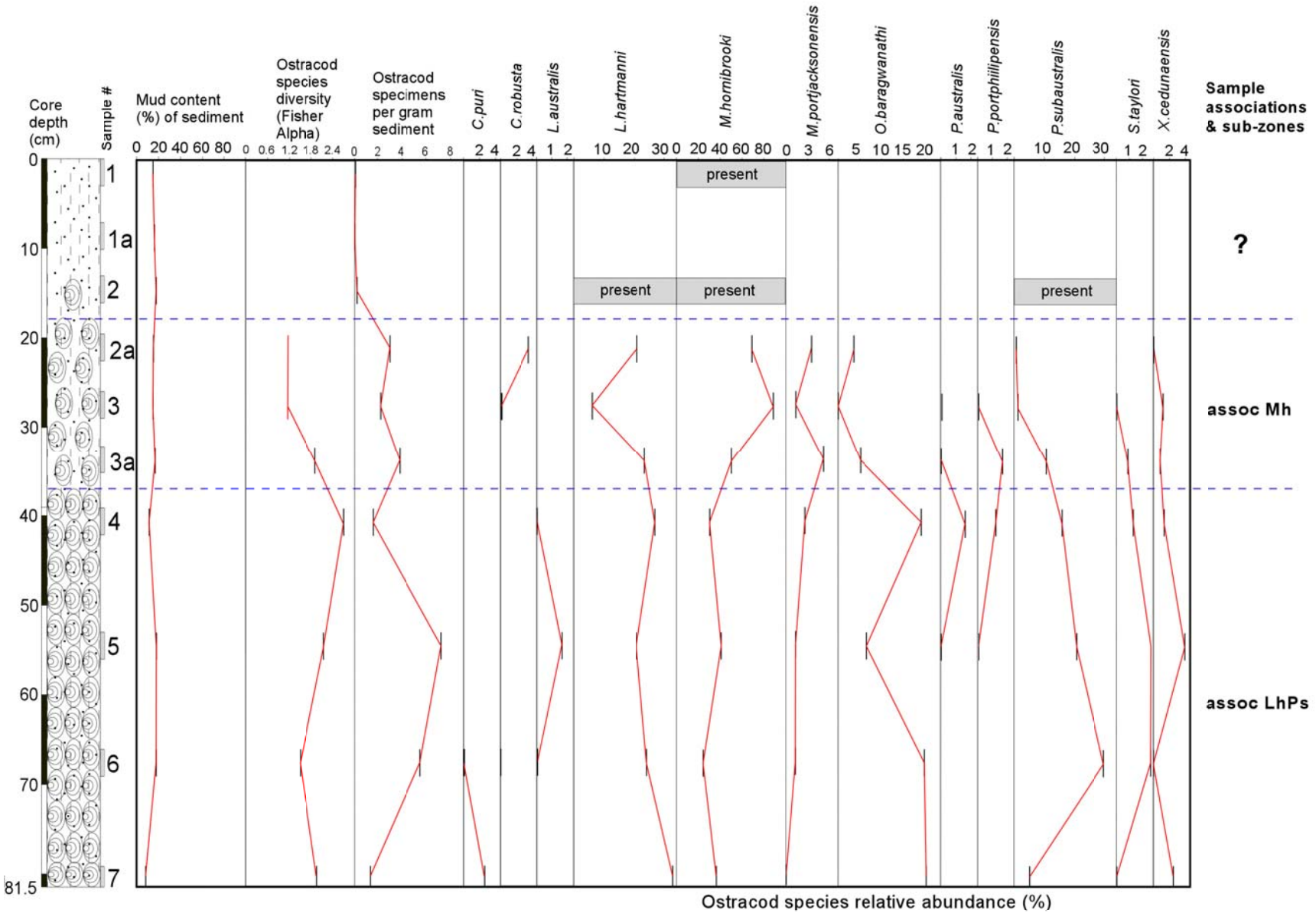

Figure 11.14. Fossil ostracod distribution in the Stinking Point core.

11.5.4.2. Sample associations and sub-zones

Cluster analysis of seven Stinking Point core sub-samples identified associations LhPs and Mh (Figure 11.14). Association LhPs is present within the highly shelly layer (81.5 – 37cm), and association Mh within the moderately shelly layer (37 – 17.5 cm). Above this level, ostracods are either too low in number to permit accurate cluster analysis, or totally absent.

(i) Association LhPs

The association is dominated by *M. hornibrooki* (abundance of 33%) with sub-dominant *L. hartmanni* (abundance of 26%). Secondary species include *P. subaustralis* (18%) and *O. baragwanathi* (16%).

The association is present in four sub-samples, within the highly shelly layer. In the modern estuary, the association occurs in shallow subtidal areas subject to freshwater influence, and of lowered pH levels typical of such waters. In the Samphire Island core, the association is present within slightly shelly muddy sand, determined by foraminiferal fauna to indicate low-intermediate pH conditions. Therefore, the presence of the association within the highly shelly layer is unusual, as it was determined by foraminifera to represent high pH conditions.

The association may relate specifically to the greater presence of *O. baragwanathi* and *P. subaustralis*, as the abundance of *L. hartmanni* and *M. hornibrooki* in the overlying association differs only in LhPs due to the greater presence of the former species in LhPs. It was noted in the Duckhole Rivulet core that *O. baragwanathi* and *P. subaustralis* are most abundant within the highly shelly layer of that core (when pH was high), but also became more abundant within overlying shell-free sediments as the pH and dissolved oxygen decreased. This indicates that the species have a preference for highly shelly sediments, or by being large species, are concentrated by size sorting, and that in the absence of dense shell layers (such as in the Samphire Island core) they are more abundant when pH and dissolved oxygen fall to low levels.

(ii) Association Mh

The association is dominated by *M. hornibrooki* (average abundance of 71%), with secondary *L. hartmanni* (17%), and minor *P. subaustralis* (5%), *O. baragwanathi* (3%), and *M. portjacksonensis* (3%).

The association is present in three sub-samples, within the moderately shelly layer. In the modern estuary, the association is indicative of intertidal areas, providing further evidence that the core location is from more exposed, or shallower palaeoenvironments, than the other cores studied.

The presence of *L. hartmanni*, *P. subaustralis*, and *O. baragwanathi* within the association indicates freshwater influence. The lower presence of *P. subaustralis*, and *O. baragwanathi* within the association, compared to the underlying association (LhPs) is probably related to the decrease from high to moderate shell content of the sediments. The increased presence of *M. portjacksonensis* within association Mh probably suggests a decrease in pH associated with declining clam shell content and increased agglutinated foraminifera content, as well as an increase in water turbidity, as the species has been found to be the most tolerant of low pH and low illumination within the modern estuarine environment.

Above the association, ostracods are of very low abundance, or absent, indicating that a decline occurred in pH down to levels which ostracods could not tolerate.

11.4.4.3. Ostracod palaeoenvironments – conditions and changes

Within the highly shelly layer, ostracods are most abundant, and pH conditions were highest. The fauna of this layer (association LhPs) are indicative of shallow subtidal waters subject to freshwater influence, as in the modern environment. Some of the species of the layer, however, appear to have a preference for the highly shelly substrate, or may be of high abundance due to post-mortem size sorting (as they are large species).

A decline in pH levels lead to a reduction in clam shell content to moderate amounts, paralleled by a decrease in ostracod abundance. The fauna of the moderately shelly layer (association Mh) is also typical of freshwater-influenced areas of the estuary, but also of more exposed, or shallower, waters than indicated by the other cores. The change in fauna between this layer and that underlying, is mainly reflected in the reduced abundance of those species which have a preference for highly shelly substrates, and by the increased abundance of one species more tolerant of lower pH and higher water turbidity.

Above the moderately shelly layer, ostracods are absent or rare, due to the lowered pH levels which caused sufficient calcite dissolution to reduce significantly clam shell content and ostracod abundance.

11.5.5. Seafloor environments – changes and links to historical activities

Due to the absence of age data for the Stinking Point core, it is not possible to describe the exact chronology of changes in sediments and fauna within the core; however, the sequence of changes can be described.

Mud content within sediments in the very shallow subtidal waters of the mouth of the Coal River, adjacent to Stinking Point, has remained low and not varied significantly since the time the base of the core was deposited. It is unknown if the sedimentation rate has varied, yet the progressive upcore loss of shell content within sediments suggests that it may have increased to some extent.

The upcore loss of clam shell content is likely to indicate (as suggested by the other cores) progressive decline of pH levels with time. Declining pH has been linked in the modern estuarine environment to nutrients or water stagnation, which lead to a reduction in dissolved oxygen levels, and hence, pH in the bottom water. Fertiliser usage is likely to be the main cause of the changes in water pH, by varying the supply of dissolved organic matter in fluvial waters delivered to the area.

The foraminiferal fauna vary mainly according to changes in pH, responding to decreasing pH by increasing agglutinated foraminifera content, and also by increasing abundance of the dominant *E. excavatum* ecophenotype relative to *A. aoteana*. The abundance of ostracod fauna reflects clam shell content, yet the faunal changes appear to be due mainly to some larger species preferring shellier sediment, or accumulating more in such sediments post-mortem. The foraminiferal and ostracod fauna do not appear to indicate any changes in salinity throughout the core.

The bottom half of the core (81.5 – 37cm) consists of highly shelly muddy sand. The high pH conditions in which this layer accumulated caused a dominantly calcareous foraminiferal fauna, allowed a high density of clam shells to accumulate, and the maximum population of ostracods.

From 37 – 17.5 cm, the core consists of moderately shelly muddy sand. The intermediate-high pH conditions of this period caused a mixed calcareous-agglutinated foraminiferal assemblage (in which calcareous foraminifera dominate), a moderate density of clam shells, and declining ostracod abundance.

Above the moderately shelly layer (17.5 – 13 cm), a slightly shelly layer is evidence of a sudden drop in pH to low levels which lead to a significant drop in clam shell content, a large increase in agglutinated foraminiferal abundance, and the disappearance of ostracods. A sudden increase in plant material during this period is evidence of an increase in the

delivery of terrestrial plant matter by fluvial flow, as well as greater nutrients of such waters derived from fertilizer runoff, which caused a reduction in dissolved oxygen levels, and therefore, a lowering of pH levels.

Above the slightly shelly layer (13 – 0cm), clam shells and ostracods are absent, indicating lowered pH levels; however, the foraminiferal fauna indicate that pH levels had risen again to intermediate levels, which currently occur at the core location.

11.6 Summary – palaeoenvironments and historical activities

11.6.1. The Midway Bay core

The core consists of sandy mud and was obtained from Midway Bay (Figure 11.15). Sediment accumulated at a rate of 0.536 cm/year before 1960, and 0.542 cm/year after. A significant increase in the accumulation of mud, relative to sand, within surficial sediments of the area occurred between 1882 and 1907, following the construction of the Midway Bay causeway in 1874, which resulted in more stagnant water conditions within Midway Bay, as tidal exchange was reduced. As the base of the core was dated 1882, the initial increase in mud accumulation following causeway construction is not recorded by the core, but probably was significantly higher. The causeway has maintained a constant effect on the seafloor environment of Midway Bay, as mud content remained relatively consistent for the rest of the 20th century.

A decline, since the 1930's, in the concentration of dissolved silica within the waters of Midway Bay (Lane, 2004), probably indicates an overall decrease in flow entering the upper estuary, coinciding with the construction of a weir at Richmond in the early 1930's.

Since at least 1884, nutrient supply to the sediments of Midway Bay is likely to have been increasing due to the increase in fertiliser (nitrogenous and phosphorus) usage throughout the catchment area during the 20th century. Increasing nutrient conditions lead to an overall increase in foraminiferal abundance, accompanied by an overall decrease in species diversity. It also promoted the abundance of the dominant species of association C over that of association Ab, such that foraminiferal association Ab (present from 1882 until the early 1950's) was replaced by association C. Association Ab originally occupied all deeper subtidal, sandy muds of the upper estuary, and not just the shallow to mid-depth subtidal, muddy sands as it does currently; whereas, association C was absent from the estuary before the early 1950's when the nutrient supply of sediments was likely to have been considerably lower than it is today.

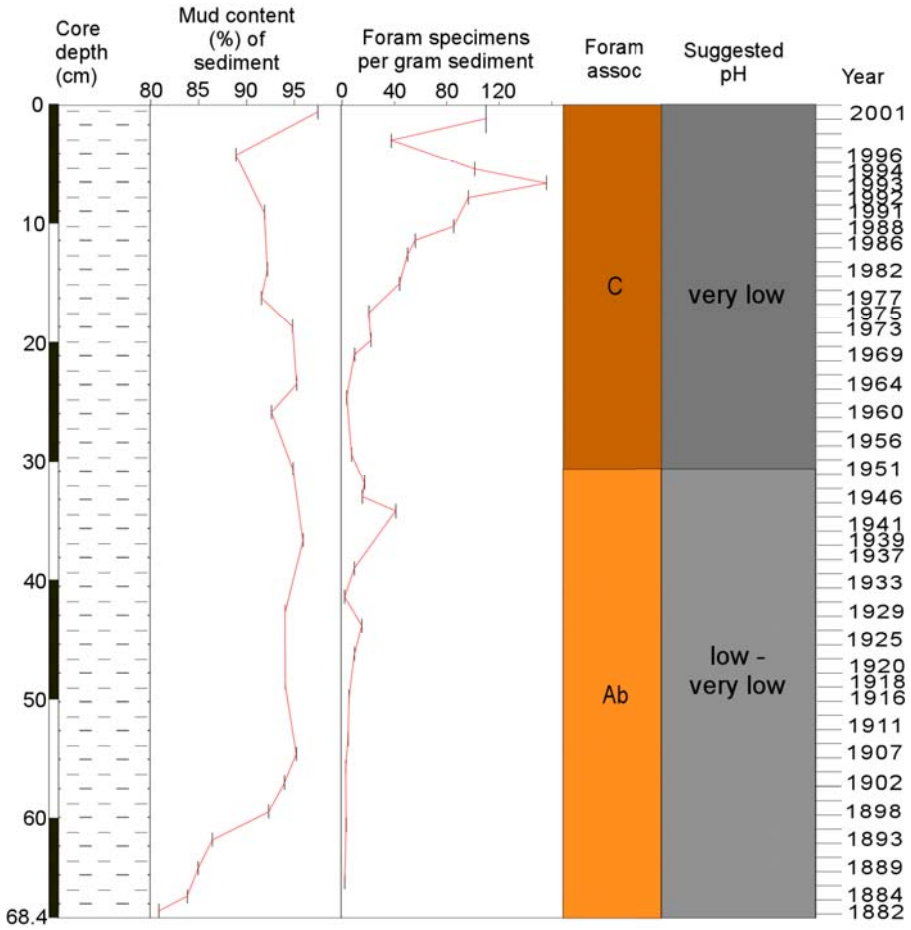

Figure 11.15. Summary of key information of Midway Bay core.

Four main periods, identified by the fauna, occur within the core, indicating different periods of inferred nutrient supply, and therefore, fertiliser usage within the catchment area. From 1882 to mid-1920's, fertiliser usage was relatively low, and had little effect on the seafloor of Midway Bay; however, from the mid-1920's to early 1950's, the introduction of superphosphate and the dominance of orchards within the catchment area, lead to peaks in nutrient content and a change in foraminiferal fauna. From the early 1950's to early 1970's, a reduction in agricultural activity is reflected by lowered nutrient content in sediments, yet the foraminiferal fauna is still different from that before fertilisers were introduced. A substantial increase in fertiliser usage occurred after the early 1970's, reaching a peak in the early 1990's after the South-east Irrigation Scheme was introduced, which drastically increased foraminiferal abundance, and further altered species composition.

11.6.2. The Duckhole Rivulet core

The core was obtained from the mouth of Duckhole Rivulet, and consists of muddy sand which is increasingly shelly with depth, featuring a dense oyster layer within the basal two thirds (Figure 11.16). A constant sedimentation rate of 0.575 cm/year was calculated for the core. Since the early 1920's, there has been an overall decrease in the oyster, clam and ostracod shell content, and an overall increase in agglutinated foraminiferal content. This indicates a progressive decline in pH levels resulting from decreasing dissolved oxygen levels, due mainly to an increasing supply of fertiliser nutrients and particulate organic matter sourced from fluvial runoff from agricultural land in the catchment area.

The dense oyster bed was present within the shallow subtidal waters of the mouth of Duckhole Rivulet from at least the early 1920's until the mid-1970's. This layer supported a high abundance and diversity of benthic species and represented a period when pH conditions were intermediate-high, and sedimentation rate was low. Within the layer, foraminifera indicate that pH was decreasing upcore.

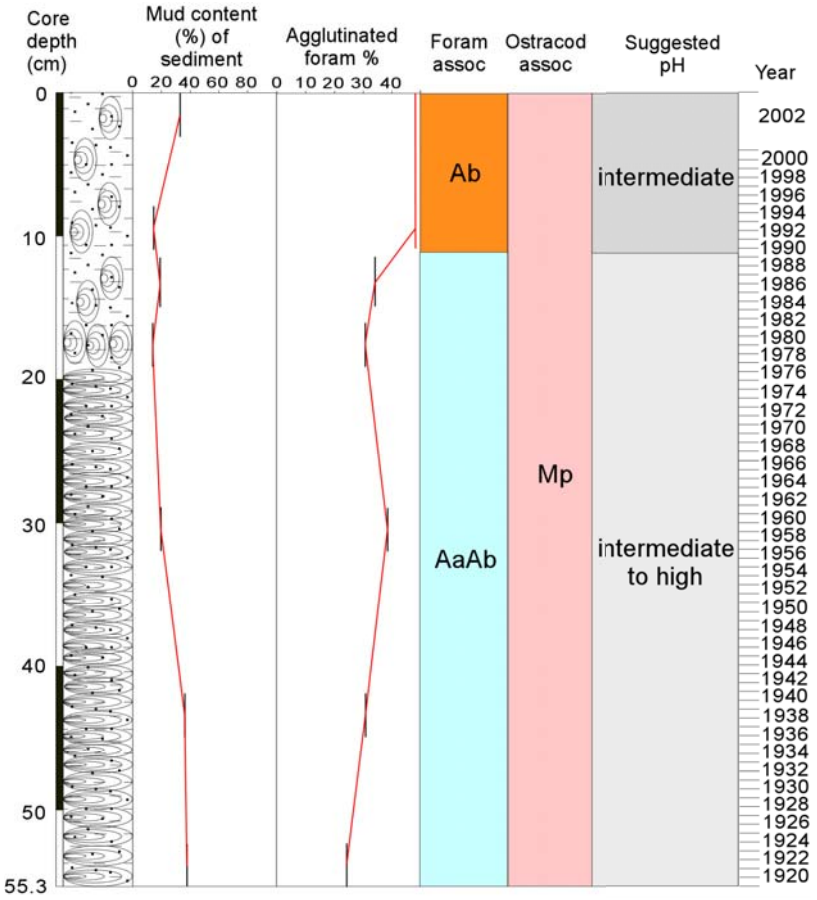

Figure 11.16. Summary of key information of Duckhole Rivulet core.

In the mid-1970's, deposition of the dense oyster layer ceased, and was replaced by a dense clam layer with minor gastropods. An increase in water turbidity and sedimentation rate is likely to have caused this transition, as clams and gastropods can cope better with higher turbidity than native oysters. However, it likely that the additional detrimental effects of declining dissolved oxygen and pH also contributed to the demise of native oysters, as the abundance of ostracods and foraminifera also dropped abruptly after deposition of the oyster layer ended. An increase in agriculture (particularly orchards) within the catchment during the first half of the 20th century is likely to have caused the increase in turbidity, as well as a gradual increase in sedimentation rate and the delivery of increased nutrients and particulate organic matter.

From the mid-1970's to the late 1980's, gradually declining pH, caused by declining oxygen concentrations, resulting from increased nutrient delivery to the area, caused increasing calcareous shell dissolution, which lead to a steady decline in clam shell content within the sediments, as well as a change in foraminiferal and ostracod species composition.

During the early 1990's, following establishment of the South-east Irrigation Scheme in the late 1980's, an increase in mud accumulation occurred on the seafloor, as well as an abrupt lowering of bottom water pH. This was probably a result of the increased delivery of nutrients and fine sediment derived from increased sediment runoff and fertiliser usage in the catchment area, following the increase in higher value irrigated cropping. However, it may also be related to increased water stagnation following construction of the Craigbourne Dam in 1985, with more stagnant conditions allowing more fine sediment settling and reducing dissolved oxygen levels. Foraminiferal association AaAb, which had been present within the core until then, was replaced by association Ab, which, with the abrupt increase in agglutinated content, indicates that pH had decreased to intermediate levels. Clam shell content was, by then, only minor within sediments. The less shelly substrate allowed seagrass to become further established in the area; however, after this, seagrass density was reduced, probably as a result of increased nutrients and turbidity. Changes in ostracod species composition since the early 1990's, suggest a further increase in water turbidity, possibly resulting from the increase in water stagnation.

11.6.3. The Samphire Island core

The core was obtained from the Coal River, adjacent to Samphire Island, and consists mainly of muddy sand, with a sandy mud layer, and a clam shell layer (Figure 11.17). The

core was dated to only half way down, with a constant sedimentation rate of 1.355 cm/year for the top half. This sedimentation rate is more than double that in the Duckhole Rivulet and Midway Bay cores, as the core was obtained directly from a river channel, where sedimentation rate appears to have been greatest.

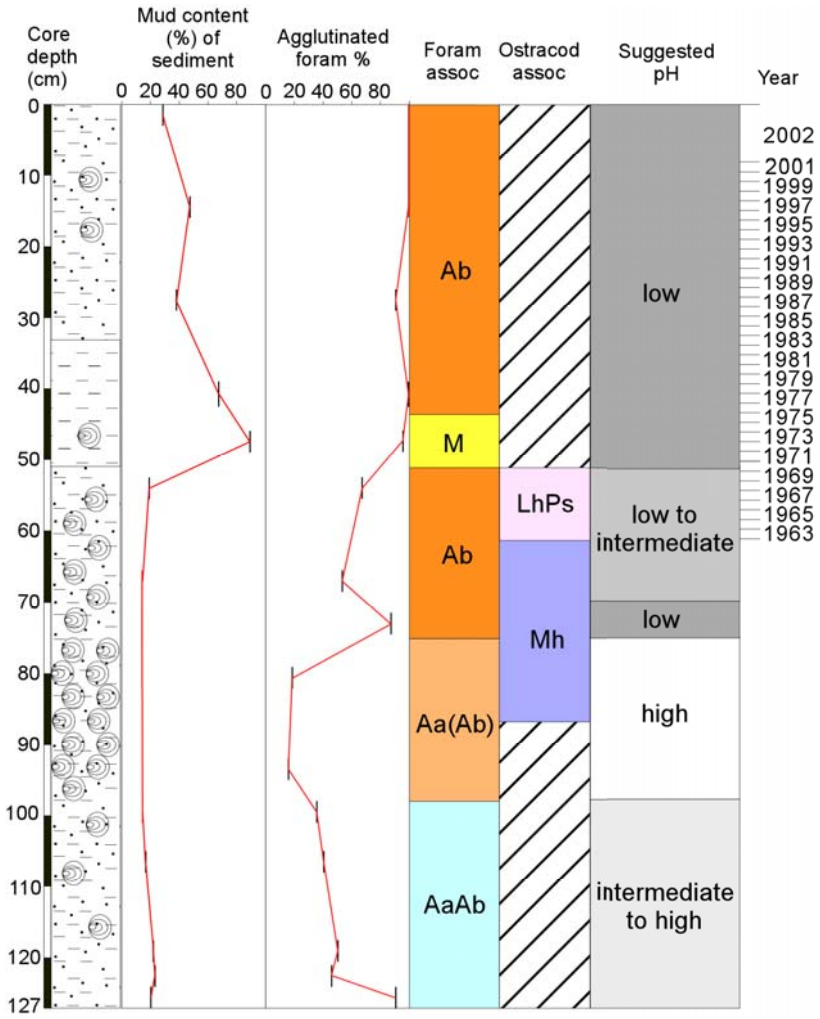

Figure 11.17. Summary of key information of Samphire Island core.

The foraminiferal fauna appear to vary mainly according to changes in pH, and to a lesser extent, changing levels of nutrient supply in sediment (correlating with mud content). Ostracods are absent from much of the core, due to long periods of low pH conditions, with associations Mh between 87 – 61 cm, and LhPs from the early to late 1960's.

Prior to the late 1960's the undated sediments were consistently muddy sand of low mud content. However, the appearance and disappearance of a clam shell layer, and significant changes in the benthic fauna, indicate a gradual increase, and then decrease, in pH. It is

likely that changes in land use are responsible for these changes in water pH, with variations in the supply of dissolved organic matter in fluvial waters delivered to the area.

The basal 25 cm of the core contains rare clam shells, no ostracods, and a mixed agglutinated-calcareous foraminifera assemblage (association AaAb) indicative of intermediate-high pH conditions. From 98 – 74.5 cm, an increase in water pH to high levels, allowed moderate clam shell layer development, and increased abundance of ostracods and calcareous foraminifera (association Aa(Ab)). From 74.5 – 70 cm, a significant drop in pH to low levels caused clam shell and ostracod content to drop significantly, and agglutinated foraminifera to become more abundant, with foraminiferal association Ab appearing. It is likely that this sudden drop in pH was caused by a significant increase in fertiliser usage within the catchment. From 70 – 53.5 cm (age unknown to late 1960's), an increase in pH to low-intermediate levels, allowed an increase in ostracod and calcareous foraminifera abundance, yet clam shells remained of low abundance in sediments.

The timing of the deposition of the clam shell layer in the Samphire Island core coincides with the oyster layer of the Duckhole Rivulet core. The significantly higher sedimentation rate within the Samphire Island core, compared to the Duckhole Rivulet core, explains why clam shell layers have been less dense than in the other core, as such would make shell content more diluted within the sediment.

Increased agricultural activity after the late 1960's caused a dramatic increase in mud content of the sediments of the Coal River, as more topsoil exposure lead to increased sediment content in runoff delivered to the upper estuary. However, the clearance of large areas within the catchment by the bushfires of 1967 is likely to have been a contributing factor. The increase in nutrient supply of the sandy mud deposited lead to a change in foraminiferal species composition (with association M appearing), increased aquatic plant growth, and a further decrease in pH which removed ostracods and clams.

From the late 1960's until the mid-1980's, the amount of mud accumulating on the seafloor of the Coal River gradually decreased, leading to further change in foraminiferal species composition (reappearance of foraminifera association Ab), indicative of the low pH conditions. Since the mid-1980's, mud content has decreased gradually, although a minor rise during the early to mid-1990s could be attributable to construction of the Craigbourne Dam and South-east Irrigation Scheme.

11.6.4. The Stinking Point core

The core was obtained from the mouth of the Coal River, adjacent Stinking Point, and consists of muddy sand with uniformly low mud content (Figure 11.18). An overall decrease in the shell content of the muddy sands occurs upcore with the presence of a basal highly shelly layer (81.5 – 37 cm), a moderately shelly layer (37 – 17.5 cm), a slightly shelly layer (17.5 – 13 cm) and a zone from which shells are absent (13 – 0 cm). The upcore loss of clam shell content of sediments is likely to be due to the progressive decline of pH levels with time, linked to increasing supply of dissolved organic matter in fluvial waters, originating from increasing fertiliser usage in the catchment area. However, an increase in sedimentation rate, and perhaps water turbidity, may also have accompanied such pH changes.

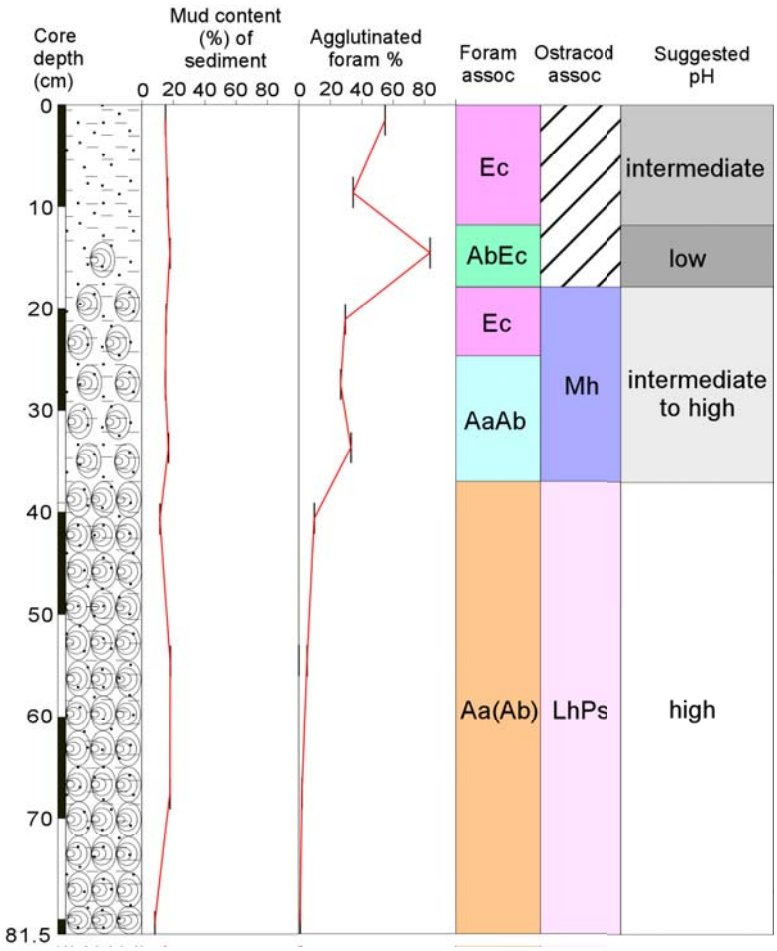

Figure 11.18. Summary of key information of Stinking Point core.

The foraminiferal fauna vary mainly according to changes in pH. The abundance of ostracod fauna parallels that of clam shell content, yet the faunal changes are mainly due to

some larger species preferring shellier sediment, or accumulating post mortem in such sediments. The fauna of the core appear to be indicative of a location more exposed, or shallower, than that of the Duckhole Rivulet and Samphire Island cores.

The bottom half of the core (81.5 – 37cm) consists of highly shelly muddy sand. The high pH conditions in which this layer accumulated caused a dominantly calcareous foraminiferal fauna (association Aa(Ab)), to be present, allowed a high density of clam shells to accumulate, and the maximum population of ostracods (association LhPs) to be established.

From 37 – 17.5 cm, the core consists of moderately shelly muddy sand. The intermediate-high pH conditions of this period lead to a mixed calcareous-agglutinated foraminiferal assemblage (association AaAb and Ec, in which calcareous foraminifera dominated), a moderate density of clam shells, and declining ostracod abundance (ostracod association Mh).

Above the moderately shelly layer (17.5 – 13 cm), a slightly shelly layer is evidence of a sudden drop in pH to low levels which lead to a significant drop in clam shell content, a large increase in agglutinated foraminiferal abundance (with the appearance of foraminiferal association Ab), and the disappearance of ostracods.

Above the slightly shelly layer (13 – 0cm), clam shells and ostracods are absent, indicating lowered pH levels; however, the foraminiferal fauna (association Ec) indicate that pH levels had risen again to intermediate levels, which currently occur at the core location.

CHAPTER 12. RECENT SEAFLOOR ENVIRONMENTS - COMPARISON OF MODERN STUDY TO PREVIOUS SPATIAL SURVEYS

12.1. Introduction

In this chapter, the recent development of the estuarine environment is investigated, by comparison of the modern environment of the present study with that described in previous spatial surveys. The first, and most important, of these spatial surveys is that of Harris (1968), in which the distribution of surficial sediments, foraminifera and ostracods were described. A second spatial survey was made by Brett (1992) on the surficial sediments of Orielton Lagoon. Also in this chapter, the geomorphological development of the estuary is briefly described, by comparison of aerial photographs collected in 1966 and 1984 with modern satellite imagery.

12.2. Sedimentological development of the estuary since 1968

By comparing the surficial sediments distribution of the 1968 spatial survey with that of the current study, the overall development of the estuarine seafloor environment since 1968 can be described. In order to make such comparisons, the sediment analysis techniques used by Harris (1968) have been replicated, such that data of similar form can be compared between both studies. Results from the current study were presented in the following format: grain size mean (phi) of sediment, grain size sorting (phi) of sediment, maximum and minimum grainsize, and relative entropy. Charts displaying the results of these analyses from the previous and present studies were compared and contrasted. Additionally, a map of generalised lithology from the 1968 study was analysed.

12.2.1. Mean grain size (phi) of sediment, and generalised lithology.

In the study of Harris (1968), sand was found to be dominant over mud, with bottom sediment mean grain size ranging from only 2.0 to 3.7 phi (Figure 12.1). Medium and fine sand grades dominated, with any variation to the mean grain size of sediment being attributed to the presence of mud or shell content, with the former increasing the mean (phi) size, and the latter decreasing the mean (phi) size. Therefore, although mud content values were not provided in the 1968 study, the mean grain size of sediment values can be used as an indirect representation of mud content.

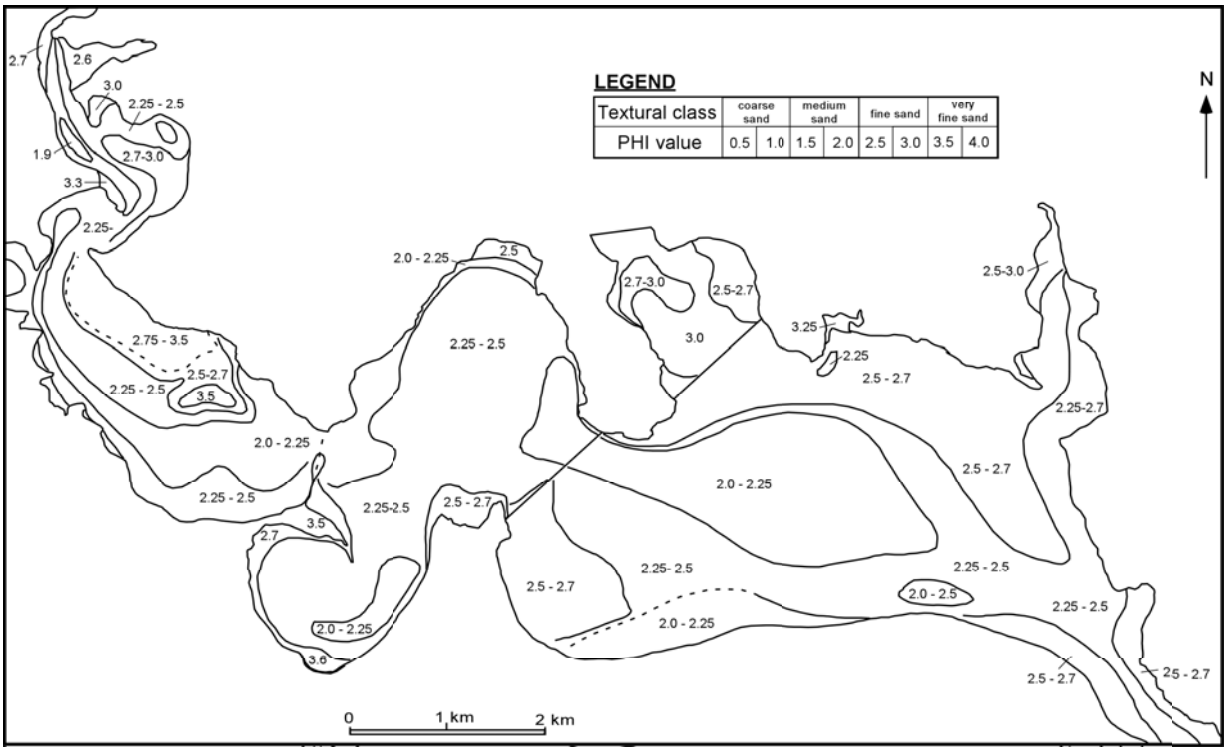

Figure 12.1. Mean (phi) diameter of sediment (from Harris, 1968).

In the present study, the mean grain size (phi) of sediment was found to range from 1.6 to 7.3 phi (Figure 12.2). This variation in the mean is also considered to represent variations in mud content, as the sand usually remains of fine to medium grade.

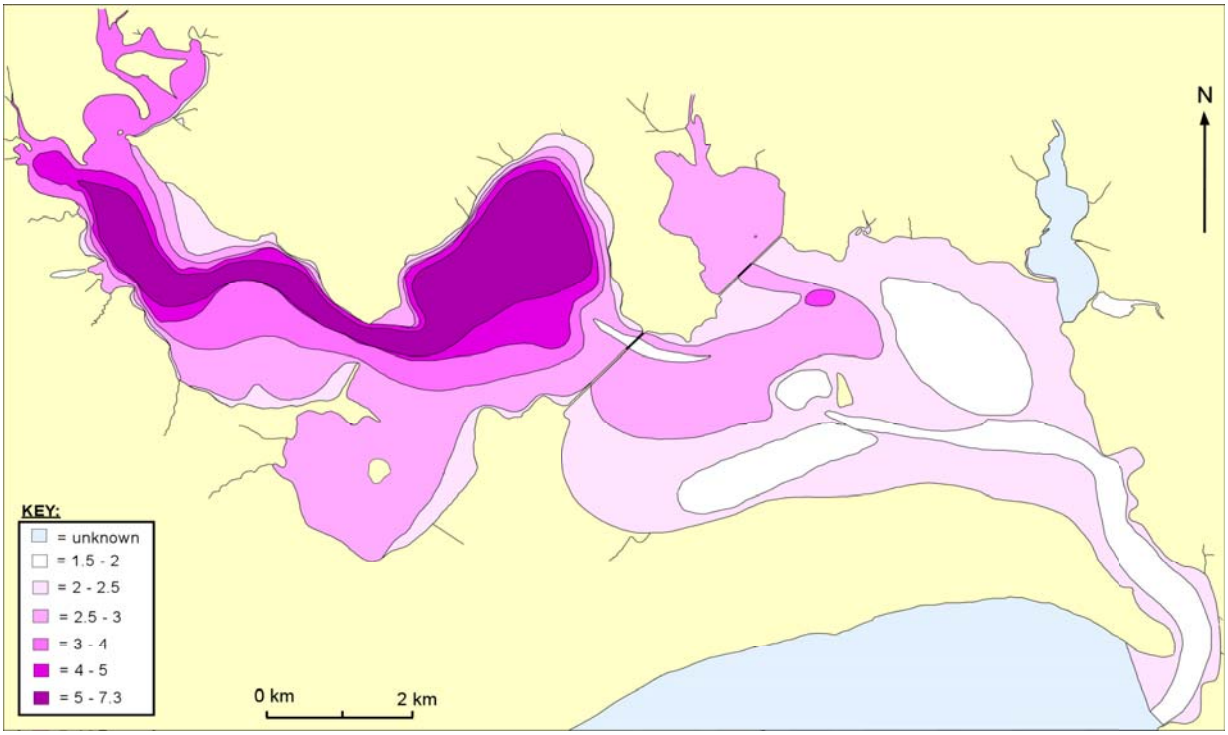

Figure 12.2. Mean (phi) diameter of sediment (in current study).

It can therefore be considered, that the greater range of these mean values indicates that mud is more abundant in the present study, than in the 1968 study, although it is difficult to specify by how much.

In the 1968 study, mean values of greater than 2.5 phi generally correlated with zones of 'sandy silt', 'sand & clay – silt', and 'sand & silty clay' displayed on the generalised lithology map (Figure 12.3). These terms were not defined, yet it can be assumed that they refer to sediment containing a mixture of mud and sand. The distribution of these zones correlates either to the present-day location of fluvial deltas and associated saltmarsh, Orielton Lagoon, or to the past or present distribution of seagrass (of which the former can be seen on the 'secondary lobe' of the Coal River delta [section 6.3.2.]; and the latter can be seen in non-fluvial delta areas of the lower estuary). The disappearance of the non-fluvial deltaic muddy sediments of the 1968 study from the lower estuary, can be attributed to the loss of seagrass, and subsequent loss of protection offered to the sediment from wave/tidal agitation. Within Orielton Lagoon, muddy sediment is still present and presently accumulating, yet any possible differences in the mud content of the lagoonal sediments between the 1968 study and the present study cannot be determined.

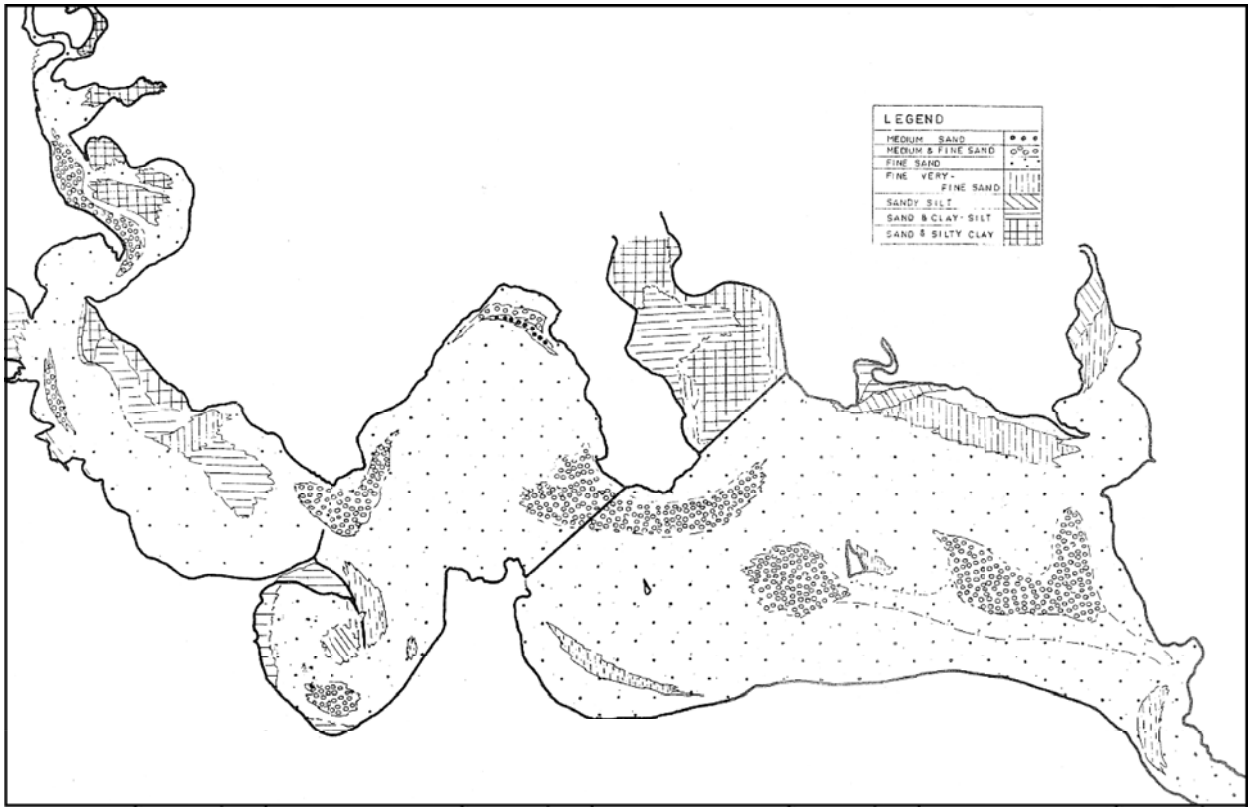

Figure 12.3. Generalised lithology (from Harris, 1968).

Within the upper estuary, the mean values of the shallower water sediments are similar to those of the present study; however, mean values of the deeper water sediments of the upper estuary are far greater, suggesting that mud is currently much more abundant within this zone (the sandy mud zone of the estuarine basin) than in 1968. This would suggest that wave action is currently minimising the accumulation of mud in the shallower waters, as it was in 1968; however, a greater supply of mud currently means that mud accumulation has increased in the deeper areas where wave action is minimal. Additionally, as described above, the 'muddier' sediments of the upper estuary in the 1968 study were confined to the fluvial deltas or intertidal areas of seagrass.

A problem, which arises from the above-described indications of the data of Harris (1968), is that within the Midway Bay core, sediments contained a high mud content during 1968, which is in direct contrast to the "fine sand" lithology of the area. For this reason, measures of mud content for the deeper areas of the Upper Estuary are treated with suspicion, and it cannot be confirmed if mud content has actually increased in these deeper areas of the upper estuary since 1968.

The map of generalised lithology (Figure 12.3) shows zones of coarser sediment ('medium & fine sand') to be within the lower estuary, confined to the causeway channel, delta head, and an area immediately north of the inlet channel, and correlate to areas of coarser sand in the marine tidal delta of the present study. The extent of the 'medium & fine sand' zone, to the immediate north of the inlet channel, is smaller than that of medium sand in the present study. Harris (1968) described the sand bars in this location as mobile, such that it is possible that sand has migrated north in this area since 1968. Additionally, the 1968 study has fine sand within the inlet channel, whereas in the present study it was measured as of medium sand grade, indicating that the present-day current strength may be greater within the channel than in 1968.

12.2.2. Minimum and maximum diameter

Minimum and maximum diameters are not commonly used as statistical measures for describing sediments. They were, however, a method used by Harris (1968) in his study of sediments in the Pitt Water Estuary. Thus, they were calculated to allow a method of comparison between the past and present studies. As in the study of Harris (1968), the phi minimum and maximum diameters were calculated for the sediment fraction greater than 0.5% of total.

Minimum modal class values are displayed in Figure 12.4, and occur within four zones: a zone of fine sand minimum modal class (2.5 – 2.75 to 2.75 – 3.0 phi) and a zone of very

fine sand minimum modal class (3.0 – 3.25 to 3.5 to 3.75 phi) both within which mud is absent; a third zone of intermediate modal class values (9 – 10 to 10 – 11 phi) very similar in distribution to that of muddy sand; and a fourth zone of finest modal class (11 – 12 phi) in a distribution similar to that of sandy mud.

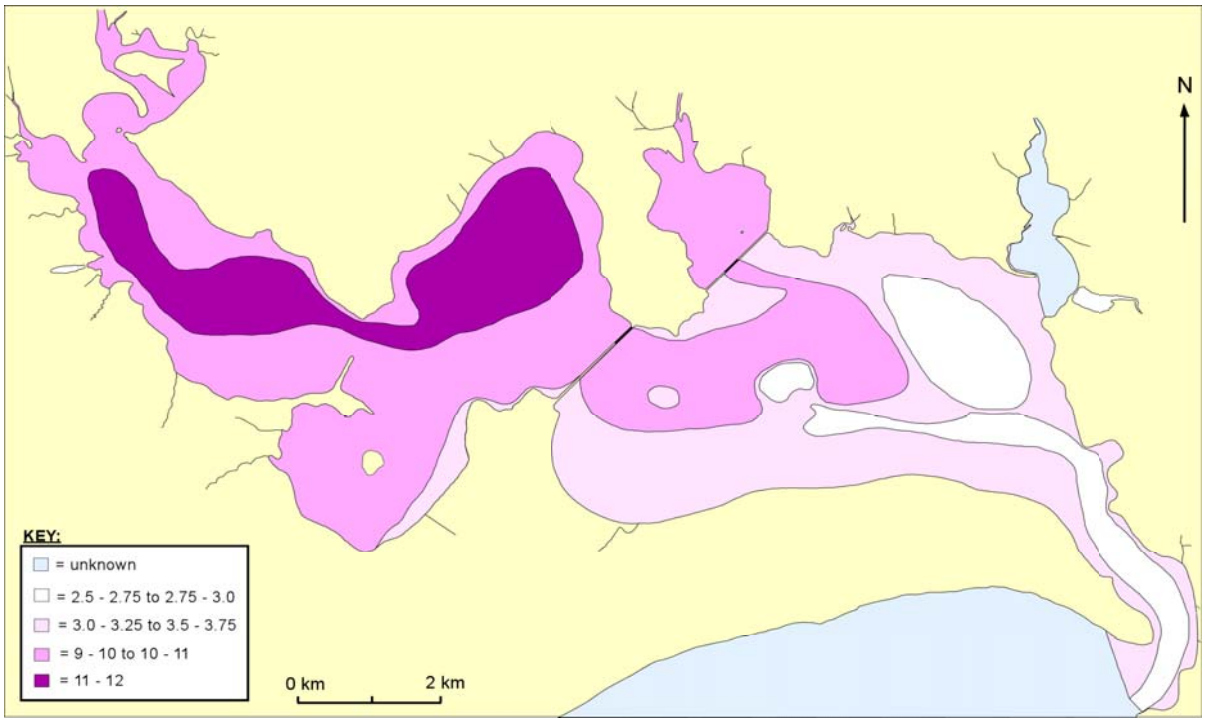

Figure 12.4. Minimum modal class (phi) of sediment fraction greater than 0.05% of total (in current study).

Figure 12.5 displays the distribution of minimum diameter in the 1968 study. From Figure 12.5 it can be seen that mud within the lower estuary was confined to a narrow zone surrounding the causeway channel which also spreads across the northern shore (the latter corresponding to seagrass distribution as mentioned earlier). It therefore appears that mud now has a greater distribution within the lower estuary than it did in 1968.

In contrast to the current study, the muddiest sediments of the 1968 study appear to have been in Orielton Lagoon. The high mud content of sediment in the lagoon is likely to have been due to the lagoon's complete separation from the lower estuary by the Sorell causeway at the time of the 1968 study. Mud supplied by Orielton Rivulet and Frogmore Creek would have been retained by the lagoon and prevented from dispersal into the lower estuary. In 1968, mud was present throughout much of the upper estuary, however it was mainly of silt grade (4.5 – 7.5 phi), with clay grade being mainly confined to restricted areas of the fluvial deltas. This would suggest that mud within the upper estuary today is much finer than it was in 1968. However, it needs to be repeated that measures of mud content for the deeper areas of the Upper Estuary are being treated with suspicion.

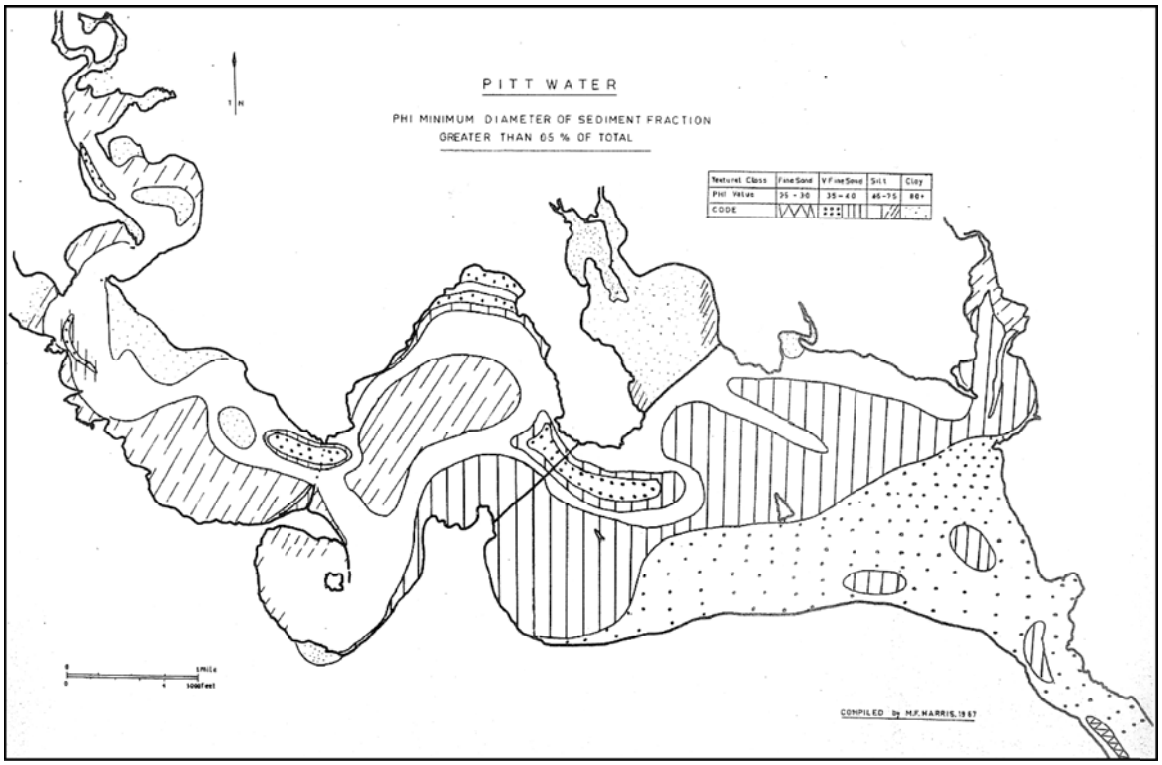

Figure 12.5. Minimum diameter (phi) of sediment (from Harris, 1968).

The maximum modal class for each sample is displayed in Figure 12.6. Values range from 0 – 0.25 phi to 2.75 – 3.0; however, the distribution of these values throughout the estuary appears to follow no obvious pattern. The only observation worthy of note is that the very finest modal class values tend to occur in the deeper areas of the upper estuary.

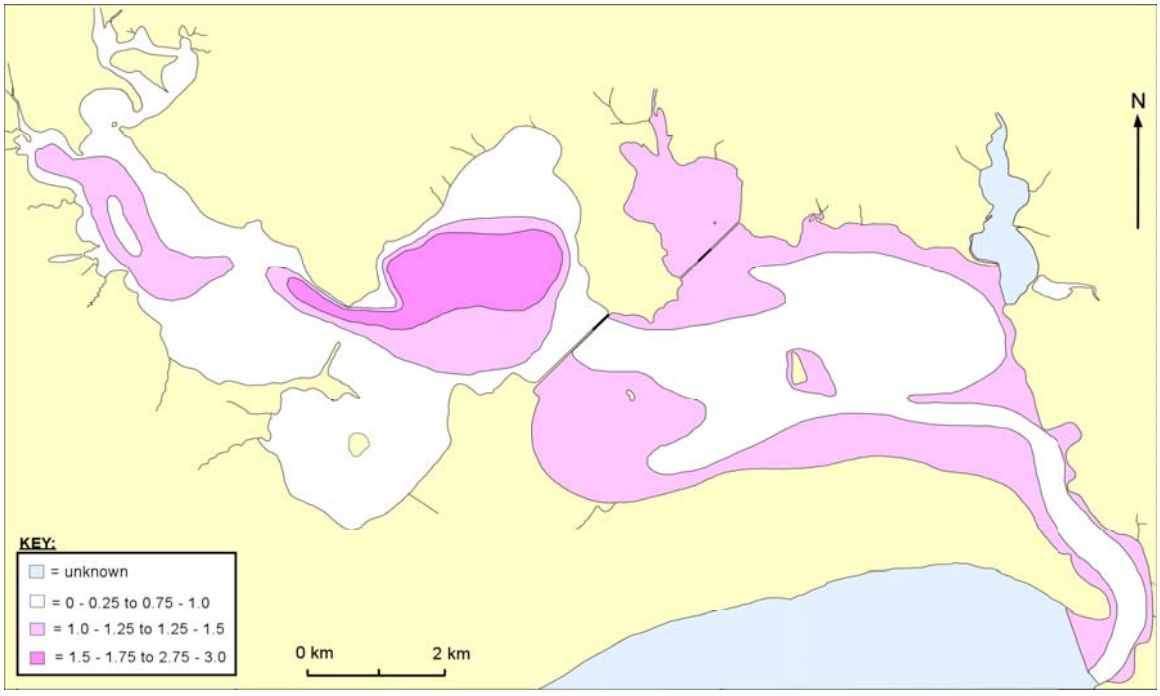

Figure 12.6. Max modal class (phi) of sediment fraction > 0.05% of total (current study).

Figure 12.6 displays some similarities to the Figure 12.7 of maximum diameter from 1968, with coarse sand being the most common maximum diameter; however, the finest maximum diameters were not found in the deepest areas of the upper estuary, as was seen in the present study.

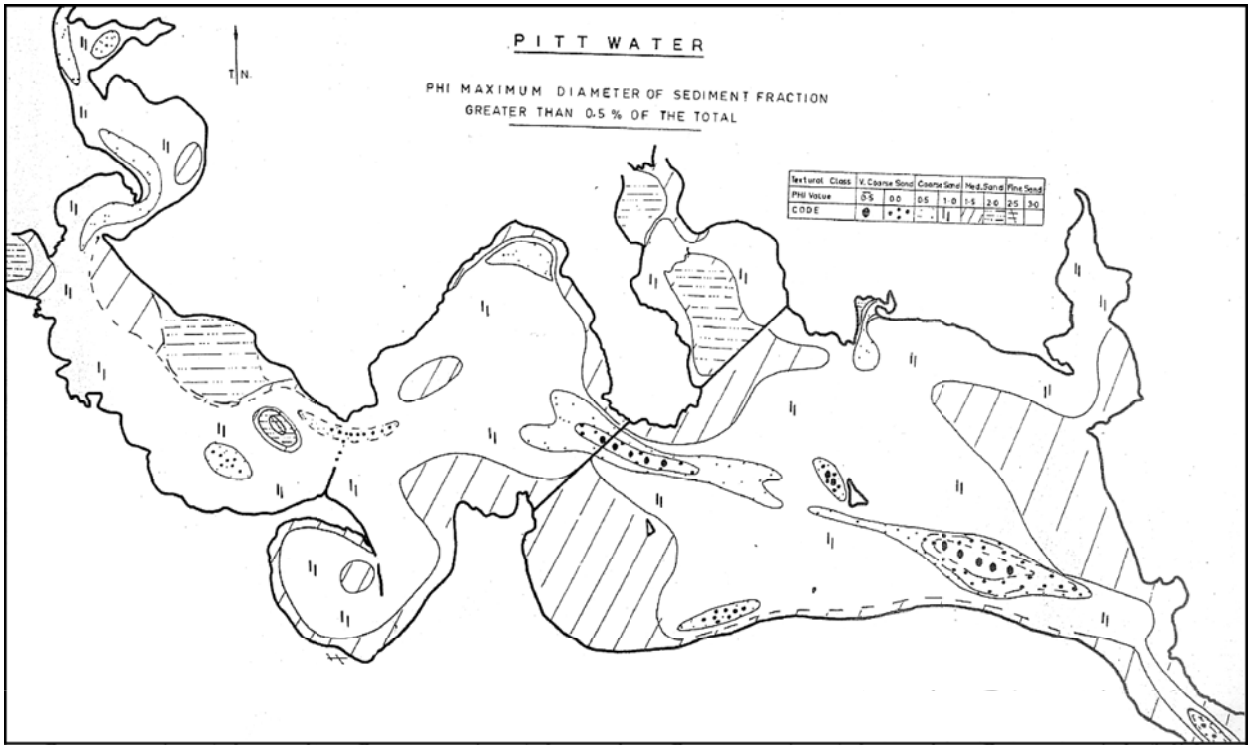

Figure 12.7. Maximum diameter (phi) of sediment (from Harris, 1968).

12.2.3. Standard deviation (sorting)

As in the study of Harris (1968), standard deviation (phi) of sediment was calculated, and used as a measure of sorting (Figures 12.8, 12.9). In Figure 12.8, there is a clear separation of sediments into three categories: moderately well to well sorted sands (SD = 0.35 – 0.7), moderately to poorly sorted muddy sands (SD = 0.7 – 2.0), and very poorly sorted muddy sands and sandy muds (SD = 2.0 – 3.0). Greater standard deviation values indicate poorer sorting, and are usually due to the presence of sand and mud.

In the study of Harris (1968), most sediments were moderately well to well sorted, with the exception being sediments from zones of greater mud content, which were moderately sorted (Figure 12.9). The greater distribution of very poorly sorted sediments, and more reduced distribution of moderately-well to well-sorted sediments, in the present study, compared to the 1968 study, may further support the conclusion that more mud is generally present within the bottom sediments of the modern environment.

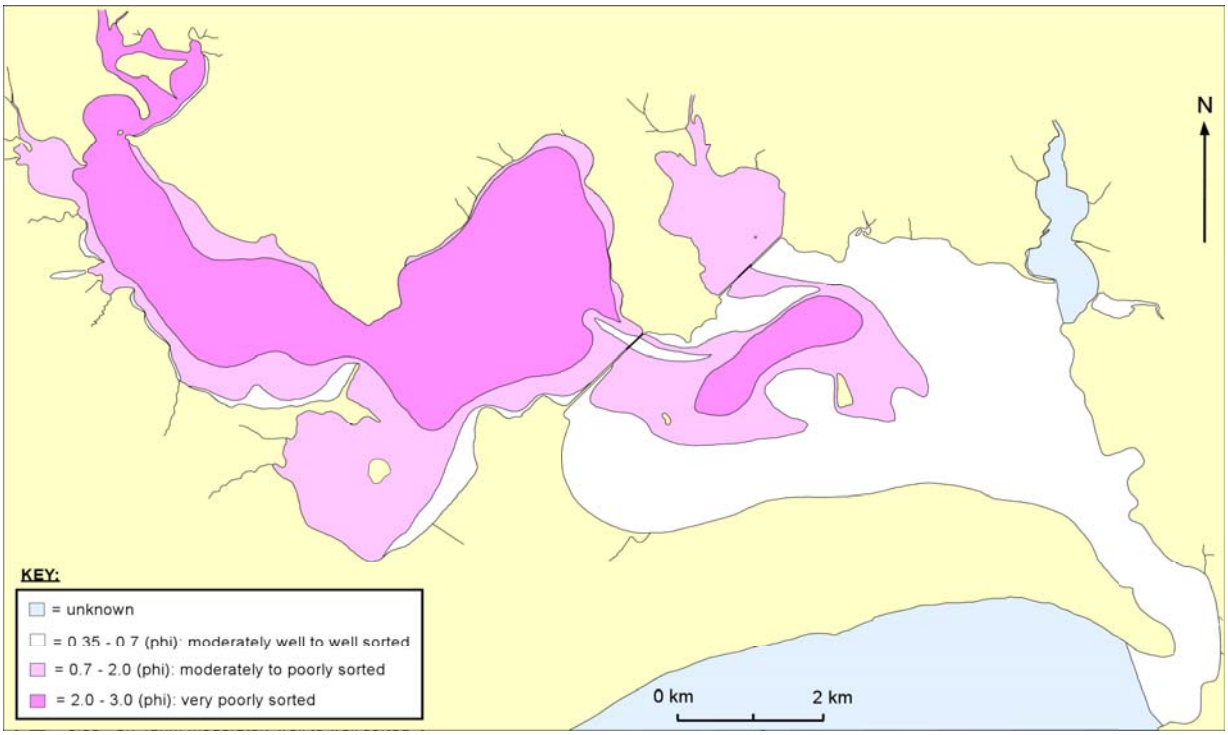

Figure 12.8. Standard deviation (phi) of sediment (in current study).

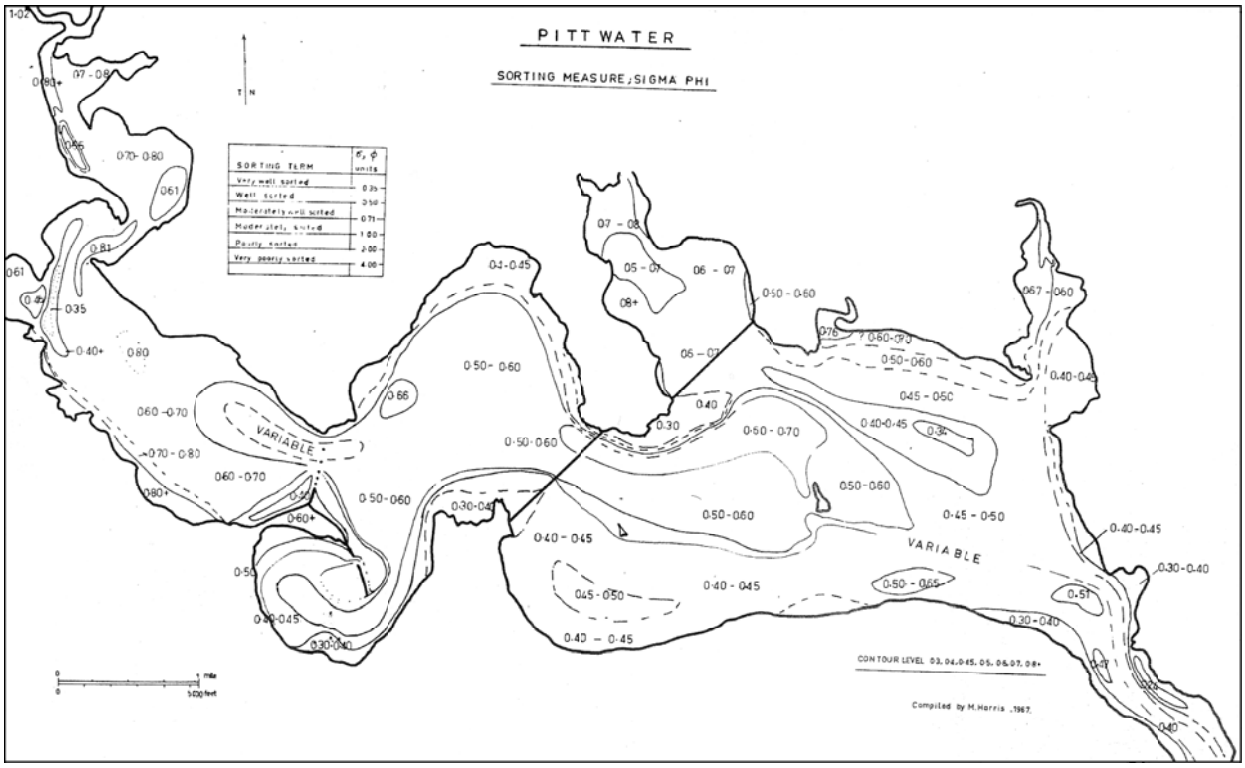

Figure 12.9. Standard deviation (phi) of sediment (from Harris, 1968).

12.2.4. Relative entropy

Entropy (defined in this study as the Shannon-Weaver information function) is a measure of uncertainty. Therefore, when calculated for sediment samples, it is a measure of within-sample heterogeneity with regard to the weight (%) values across the range of size classes. Because uncertainty is a cause of randomness, higher entropy values should occur where samples have been exposed to more uncertain conditions, and thus have a greater spread across size classes, and are therefore more poorly sorted. Relative entropy is the ratio of actual entropy to the maximum entropy which can be obtained with the same set of components (Pelto, 1954). The maximum entropy occurs where the weight (%) values for each of the 34 size classes, within a sample, are equal. Therefore, relative entropy is calculated as follows:

$$\text{Entropy } (H) = - \Sigma\, p_i \ln p_i$$

$$\text{Maximum Entropy } (H_m) = - 34 ((1/34) \times \ln (1/34))$$

$$\text{Relative Entropy } (\%) = (H / H_m) \times 100$$

Figure 12.10 displays the distribution of relative entropy values per sample within the present estuary. There are three zones of relative entropy value ranges: a zone of 55 – 65%, mainly consisting of clean sands; a second zone of 65 – 75%, consisting of muddy sands; and a third zone of 75 - 85%, consisting of muddy sands and sandy muds. Samples with the greatest relative entropy within the upper estuary tend to be located in the deeper locations, although there is an inconsistency to this apparent distribution.

There are similarities between the distribution of standard deviation and the distribution of relative entropy, due to both being measures of sorting. Both define lower values within a well defined zone which contains clean sands, and within the upper estuary the zone of highest SD values is similar in distribution to those of highest relative entropy.

In the present study, relative entropy values are generally greater than those of the 1968 study. This is due to the greater number of size intervals in this study (34 rather than 10), such that the maximum entropy is significantly greater. Figure 12.11 displays the distribution of relative entropy within the estuary of 1968. Harris (1968) described the poorly sorted sediments with high entropy values to be those of ‘sandy silts’ and ‘clay-silts’ (see 6.5.5.1). Generally, higher relative entropy values are found in the muddy sediments of the fluvial deltas and seagrass environments.

The distribution of relative entropy sediments further confirms that mud content has changed in distribution and abundance since 1968.

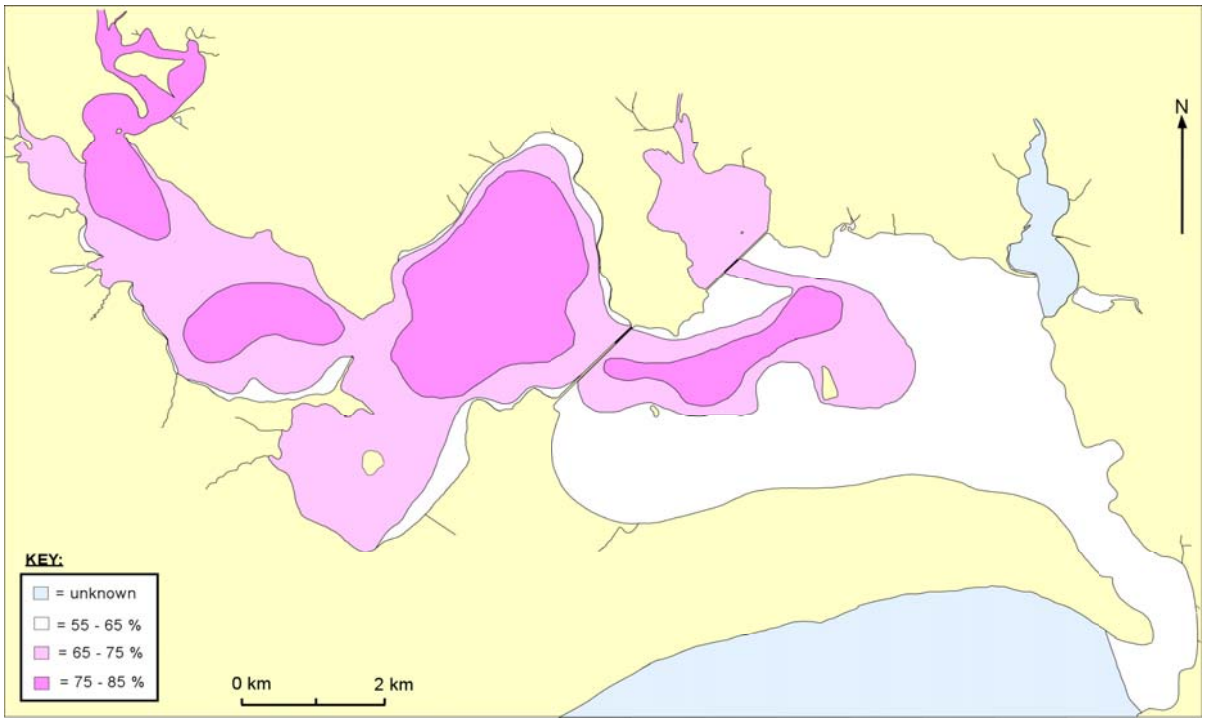

Figure 12.10. Relative entropy (%) of sediment (in current study).

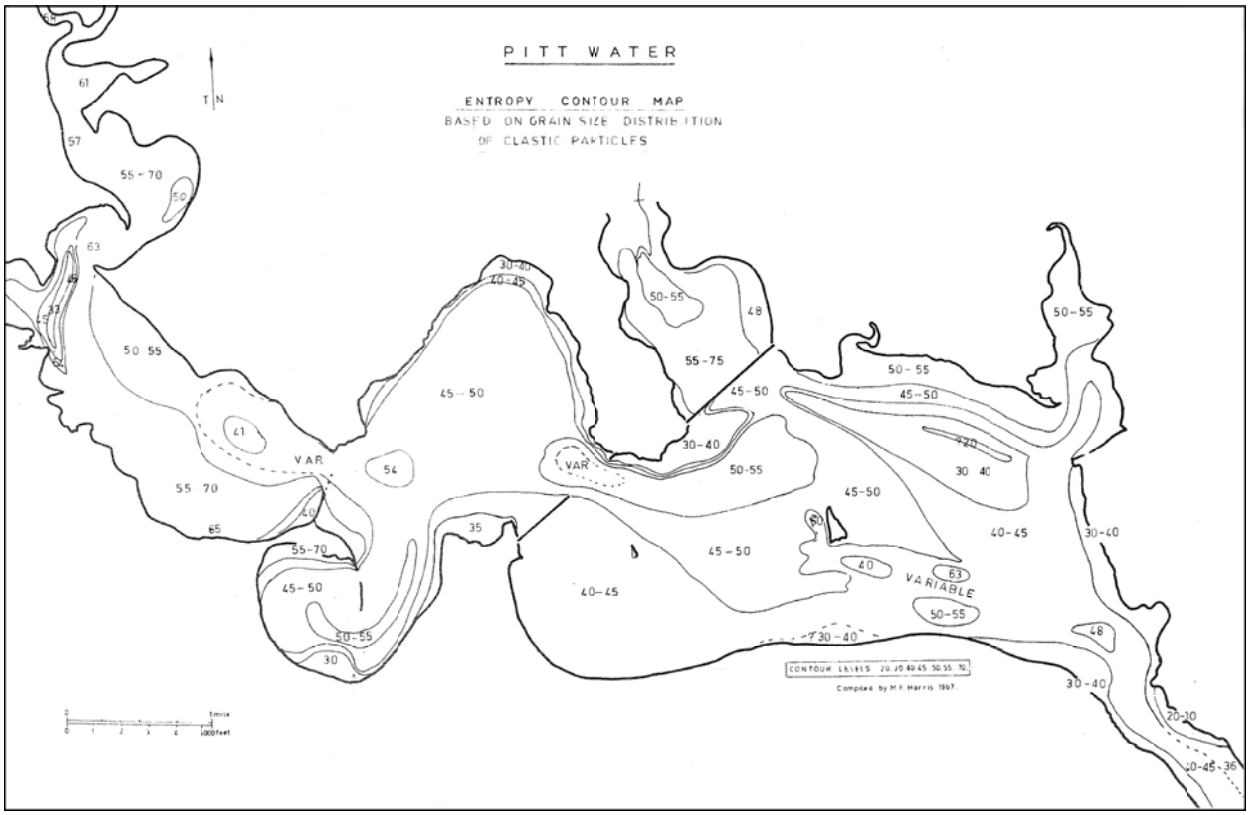

Figure 12.11. Relative entropy of sediments (from Harris, 1968).

12.3. Sedimentological development of Orielton Lagoon since 1991

In a study by Brett (1992), bottom sediment samples were obtained periodically from nine locations within the Orielton Lagoon over February, March, May, and September 1991 (Figure 12.12). Particle-size analysis was performed upon these samples, and data was divided into sand and combined clay-silt components. As the Orielton Lagoon samples of the current study were obtained in August, these results have been compared to those of September in the earlier study. However, comparison between the results of the 1992 study and the present study is limited, as only two sediment samples were obtained from the lagoon in the later study.

As the sample sites of the current and previous studies have different locations, sites of similar water depth were compared, as this controls the mud content of the bottom sediments (see 6.3.3.1). Sample # 84 of the current study is located at a similar water depth to site # 4 of the 1992 study, and both are situated on the eastern shore of the lagoon. Site # 4 was not sampled in September of 1991; however, an average taken for February, March, and May indicates a mud content of 6%, ranging from 2 – 8%. Sample # 84 of the present study had a higher mud content of 16%.

Sample # 88 of the present study is located at a similar water depth to sites # 3 and # 6 of the earlier study. Sediment samples obtained from these sites in September 1991 contained 21% and 19% mud, respectively. Sample # 88 contained 17% mud.

The above comparisons are not entirely reliable, but do reveal that the mud content of sediments in the shallower water zone of the lagoon has not changed significantly since 1991. However, any changes expected to have occurred since the lowering of culverts in 1993 (and hence, increased flushing efficiency of the lagoon) would perhaps best be detected in muddier sediments found in the deeper, central area of the lagoon (in which site # 5 was located).

12.4. Recent geomorphological development of the estuary

Visual comparison of aerial photographs taken of the Pitt Water Estuary in 1966 and 1984, and of satellite images taken in 2002, found no obvious change to the geomorphology of the estuary to have occurred since 1966. Comparison of ‘bedforms’ maps constructed of the estuary from this study, and from Harris’ 1968 study, also found no changes in the distribution and/or form of bedforms (such as sand bars) since 1968. This suggests that sand transport within the estuary is in a state of equilibrium, without any

active migration leading to the formation of new, or more developed, large-scale sedimentary structures.

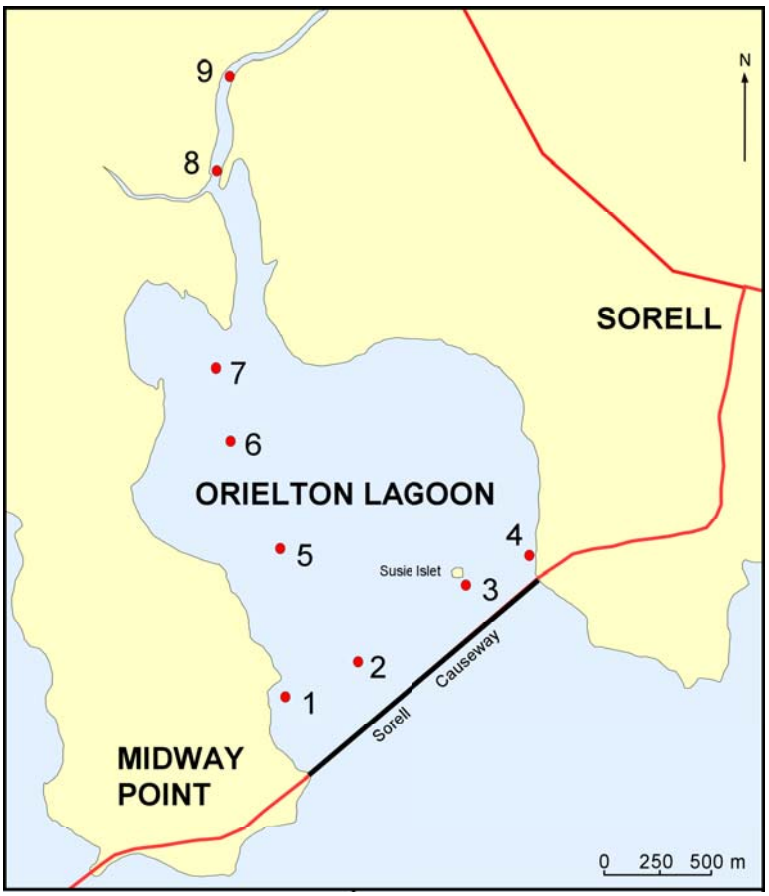

Figure 12.12. Sample site locations of Brett (1992) within Orielton Lagoon.

However, from aerial photography and GIS analysis, Watt (1999) found, in a study of the sediment transport dynamics of the Seven Mile Beach Spit, that significant changes in shoreline position have occurred to the spit during the past fifty years. It was found that the toe of the spit was migrating eastwards into the channel, while episodic retreat on the southern side and deposition on the northern side occurred (Watt, 1999). In this study, a relationship was found between shoreline retreat and marram grass invasion along Seven Mile Beach, reflecting a change in sediment transport equilibrium between the foreshore and primary dune interface.

12.5. Changes in benthic fauna since 1968

12.5.1. Summary of the results of foraminiferal and ostracod analysis by Harris (1968)

As with surficial sediment distribution, comparison between the distribution of benthic foraminifera and ostracods in the 1968 study with that of the current study, can be used to describe the overall development of the seafloor environment of the estuary since 1968.

Harris (1968) sampled 56 stations for foraminifera and Ostracoda within the estuary, and analysed 50 grams of dry sediment from each sample, with specimens being floated off with carbon tetrachloride. A total of 34 species of foraminifera and 12 species of ostracods were identified. Species diversity (Fisher α index), abundance, and relative abundance of agglutinated foraminifera, and the ratio of Ostracoda to foraminifera have been calculated for each sample using information provided in the thesis of Harris (1968).

Table 12.1 displays a list of the foraminiferal species identified by Harris (1968). *Ammonia beccarii* and species of *Elphidium* (mainly *E. incertum*, but also *E. macellum* and *E. crispum*) were the most abundant calcareous foraminifera throughout the estuary, yet *Miliolinella subrotunda* and *Quinqueloculina simplex* were relatively common. *Miliammina arenaea* was the most common agglutinated species.

Table 12.2 displays a list of the ostracod species identified by Harris (1968). These species were only been identified down to genus level, and only *Loxoconcha* and *Microcythere* (considered equivalent to *Microcytherura*) were also identified in the current study. *Leguminocythere* sp.1, *Loxoconcha* sp. and *Urocythereis* sp. were described by Harris (1968) as being very common throughout the estuary, except at the landward and seaward limits and in the channels.

12.5.2. Comparison of foraminifera and Ostracoda of current study with 1968 study

In order to compare effectively the benthic fauna data of the present study to that of Harris (1968), a consistent taxonomy is required. Unfortunately, it is not known which taxonomy Harris (1968) followed, however, there were three foraminiferal references used: Phleger (1960, 1964, 1965). Some of the species were found in the plates of these references, yet a number were not. Therefore, possible modern taxonomic equivalents are listed, tentatively, in tables 12.1 and 12.2, and only the distribution of the main species

(and a few certain minor species) of Harris' 1968 study will be discussed and compared to the distribution of their likely equivalents from the current study.

Species identified in study of Harris (1968)	Possible modern equivalents from current study
A.calcareous	*A. barwonensis*
Acervulina inhaerens	?
Ammobaculites sp.	*A. barwonensis*
Ammonia beccarii	*Ammonia aoteana*
Bulimina marginata	*Bulimina marginata*
Cancris sp.	?
Cibicides sp.	*Cibicides refulgens*
Cribroelphidium poeyanum	*E. excavatum excavatum*? *E.lene*?
Discorbinella subbertherloti	*Rosalina* sp.?
Elphidium cf.macellum	*Elphidium macellum*
Elphidium crispum	*Elphidium crispum*
Elphidium incertum	*Elphidium excavatum* ecophenotypes
Eponides tumidulis	*A. perlucida*?
Fissurina sp.	*Fissurina fasciata carinata, F. globoscaudata*
Florilus sp.	*N. auris?*
Guttulina regina	*Guttulina regina*
Haplophragmoides canariensis	*A. barwonensis* (broken coiled portion)
Lagena sp.	*L. doveyensis, L. spiratiformis, L. sulcata peculilaris*
Lenticulina sp.	*L. limbosa*
Miliammina arenaea	*Miliammina fusca*
Milliolinella subrotunda	*M. circularis, M. lakemacquariensis, M. pyrgoformis*
Pileolina zealandicus	*A. pustulosa*?
Q.cf.seminula	*Q. seminula*
Q. simplex	?
Q. striatula	*B. striatula*?
Quinqueloculina cf.bosciana	?
Recurvoides sp.	*H. wilberti* ? *P. bartrami*? *P. sorosa*?
Reophax cureta	*Cuneata arctica*
Rosalina bilardeboana	*Rosalina* sp.?
Rosalina sp.	*Rosalina* sp.?
Rosalina terqulina	*Rosalina* sp.?
Textularia sp.	*Textularia earlandi*
Trochammina inflata	*Trochammina inflata*

Table 12.1. List of foraminiferal species identified in study of Harris (1968), with possible modern equivalent species identified in the current study.

Species identified in study of Harris (1968)	Possible modern equivalents from current study
Cyprideis sp.	?
Cytheretta sp.	?
*Cytheridea (*cf. *aoteana)*	?
*Cytheridea (*cf. *mosaica)*	?
Eucythere sp.	?
Leguminocythere sp.1.	?
Leguminocythere sp.2.	?
Loxoconcha sp.	*L. australis, L. cumulus, L. gilli*
Loxoconchella sp.	?
Microcythere sp.	*M. hornibrooki, M. triebeli, M. australis*
Quadracythere sp.	?
Urocythereis sp.	?

Table 12.2. List of ostracod species identified in study of Harris (1968), with possible modern equivalent species identified in the current study.

12.5.2.1. Species diversity

In the 1968 study, species diversity was generally similar for foraminifera and ostracods, with values in the former ranging from 0.14 to 5.57 and averaging 1.64 (Figure 12.13), and values in the latter ranging from 0.16 to 7.99 and averaging 1.80 (Figure 12.14). Trends in species diversity were also similar between foraminifera and ostracods, being least in the Orielton Lagoon (averaging 0.45 for foraminifera, and 0.17 for ostracods) and greatest within the lower estuary (averaging 2.25 for foraminifera, and 2.13 for ostracods). Within the upper estuary, species diversity averaged 1.50 for foraminifera and 1.47 for ostracods, and was least in the intertidal zone and in the deepest areas.

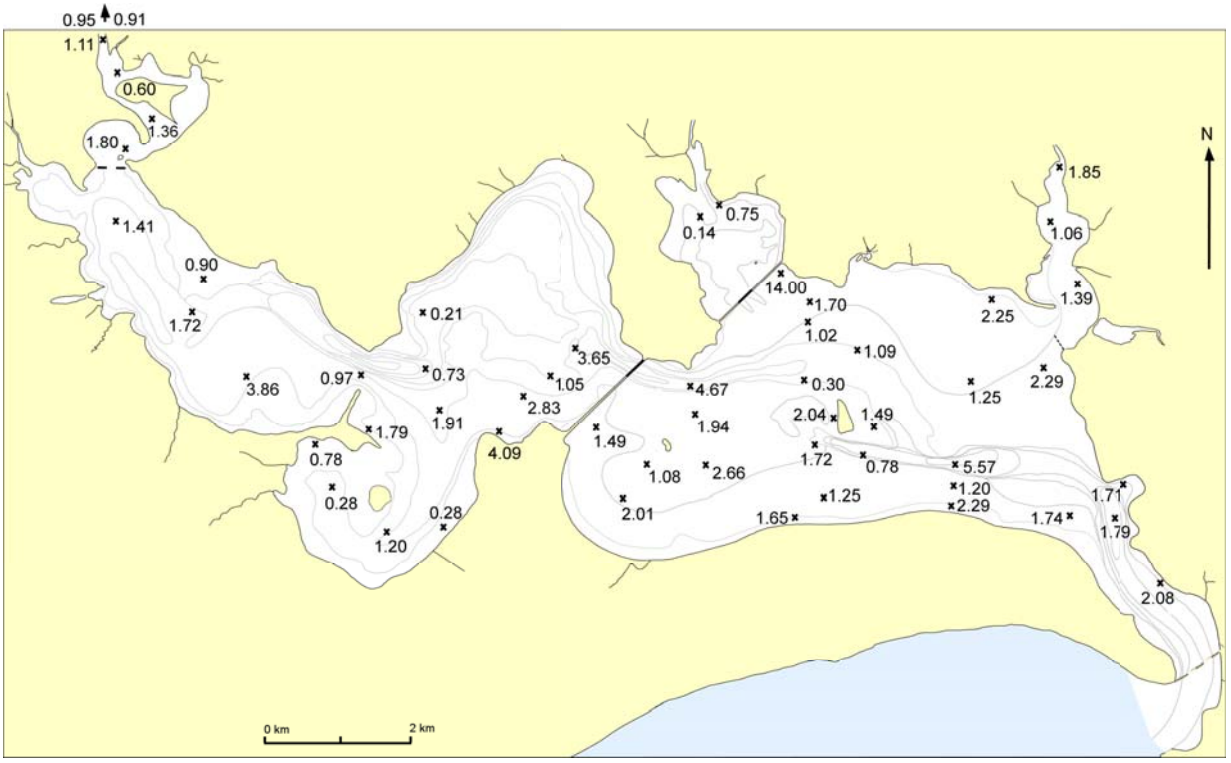

Figure 12.13. Species diversity (Fisher α Index) of foraminiferal samples (Harris, 1968).

By comparing Figure 12.13 with Figure 7.2, and Figure 12.14 with Figure 8.2, it can be seen that species diversity has remained greatest within the lower estuary, and least within Orielton Lagoon; however, it has generally increased within the estuary, and more so within the lower estuary than within the upper estuary. Within the lower estuary, species diversity has increased significantly within the marine-influenced area, and most of all within the muddiest parts of it; however, very shallow subtidal and intertidal areas away from the mouth appear unchanged. Within Orielton Lagoon, species diversity may have increased slightly, although comparative sites are in different positions. Within the upper

estuary, diversity has increased slightly, mainly within the muddiest areas (specifically, the main zone of sandy muds) and within Barilla Bay.

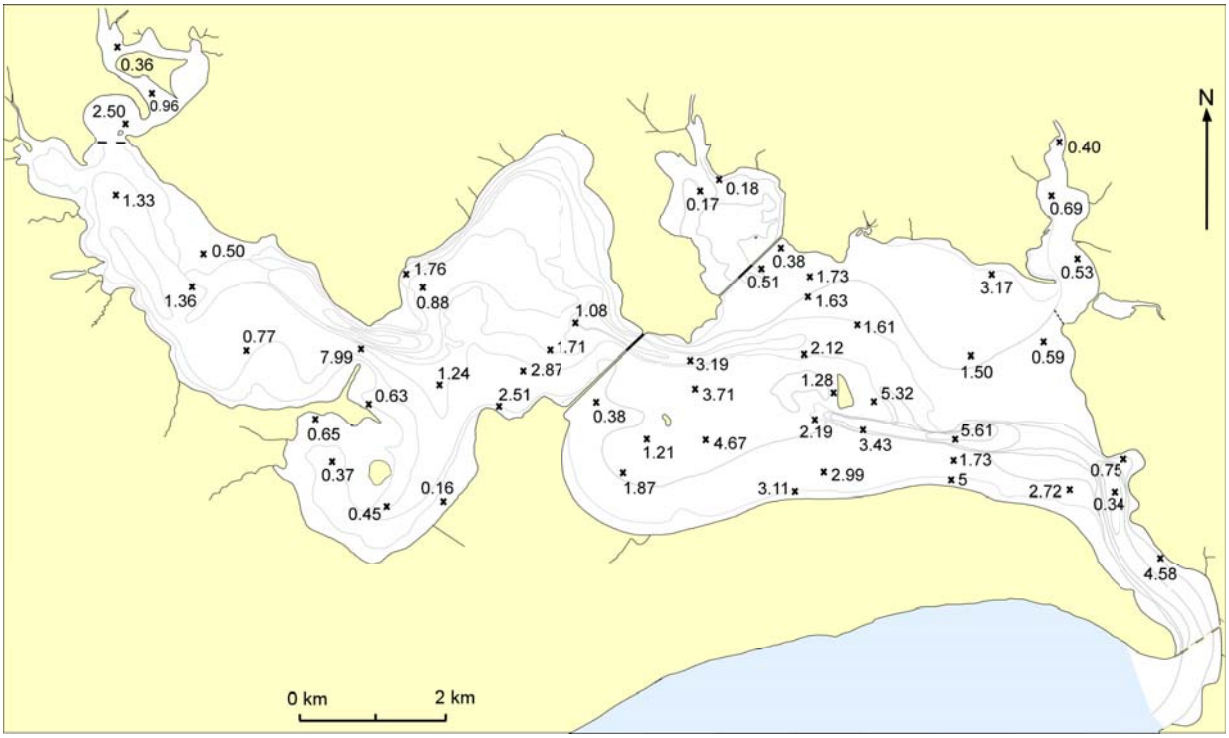

Figure 12.14. Species diversity (Fisher α Index) of Ostracoda (Harris, 1968).

The general increase in species diversity within the estuary since 1968 appears to have been greatest within those areas of the estuary which are now the muddiest. In those shallower areas of the lower estuary, where clean sands still occur, diversity has remained unchanged. This suggests that marine influenced areas are now more landward than they were in 1968.

If flooding events have decreased in magnitude and frequency since 1968 (mainly by the construction of Craigbourne Dam), then fauna typical of more marine conditions would now penetrate further landward into the estuary from the mouth. The reduction in the downstream extent of Coal River flooding, and consequent downstream extent of such influence upon faunal composition, would lead to an increase in species diversity in the marine-influenced area of the lower estuary. One could also expect a slight increase in diversity in areas of the upper estuary, due to greater penetration upstream by marine waters. This would explain why diversity has increased less within the upper estuary than within the lower estuary (and only slightly). A slight increase in diversity within Orielton Lagoon, may have occurred due to lowering the culverts of Sorell Causeway, which would

have reduced environmental stress, and increased exchange with the currently more upstream-reaching marine waters.

Therefore, the areal extent of estuarine conditions is now more reduced than in 1968, and the influence of marine conditions originating from Frederick Henry Bay penetrate further upstream, although the Midway Point Causeway still prevents further upstream penetration into the upper estuary.

12.5.2.2. Faunal abundance

In the 1968 study, foraminiferal abundance ranged from 0 to 11 specimens per gram of dry sediment (Figure 12.15), averaging 1.94; whereas, ostracod abundance ranged from 0 to 31 specimens per gram dry sediment (Figure 12.16). Foraminiferal abundance was generally greater within the lower estuary (average of 2.19) than within the upper estuary (average of 1.53), and greatest within Orielton Lagoon (average of 2.98). In contrast, ostracod abundance was generally greater within the lower estuary (average of 1.23) and Orielton Lagoon (1.18) than within the upper estuary (1.53).

Trends in foraminiferal abundance within the estuary in 1968 are hard to find, although in some areas it appears to decrease in shallowing water. However, it was clearly greatest within the estuary mouth, reflecting the less stressful conditions of the more marine areas of the estuary at that time.

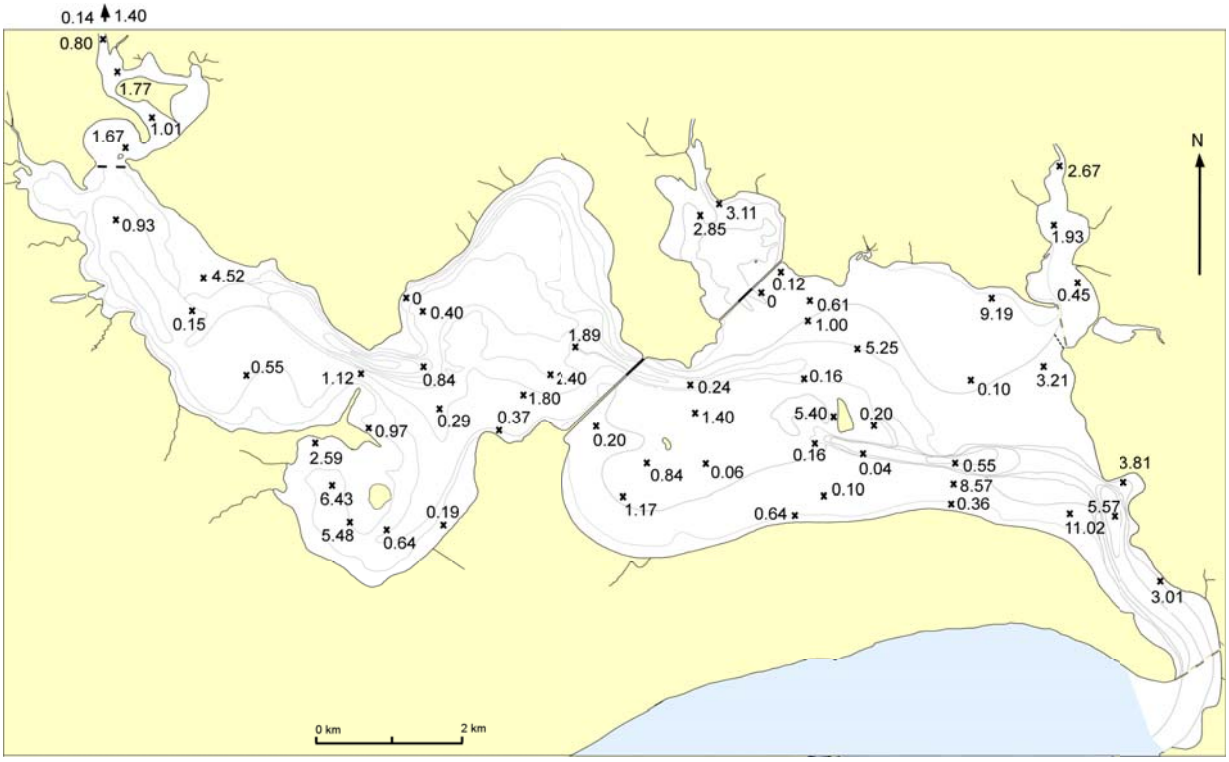

Figure 12.15. Foraminiferal abundance (specimens/gram of dry sediment) (Harris, 1968).

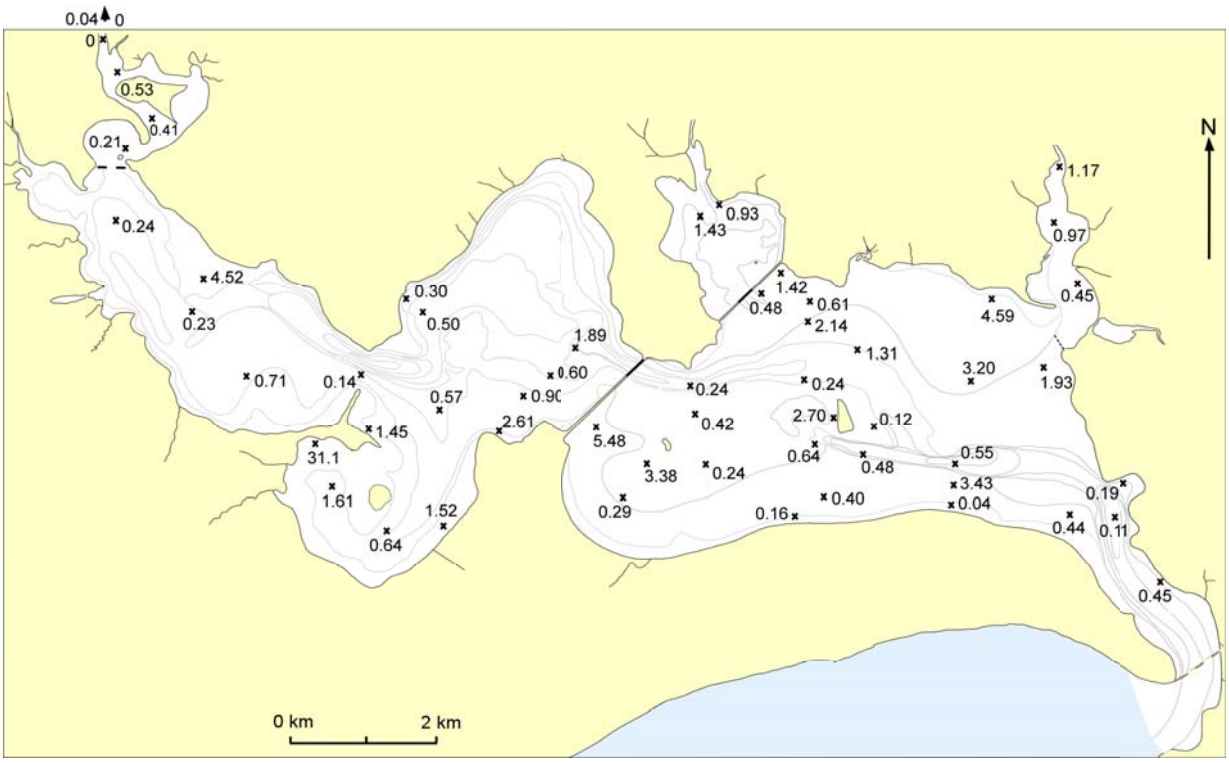

Figure 12.16. Ostracod abundance (Specimens per gram of dry sediment) (Harris, 1968).

By comparison of Figure 12.15 to Figure 7.3, and Figure 12.16 to Figure 8.3, it can be seen that foraminiferal and ostracod abundance within the still clean sands (outside of the channels) of the estuary today, has remained the greatest within the mouth. However, abundance has increased to some degree within the clean sands of the lower estuary, most of all in those locations proximal to areas of constricted water flow (i.e. near the opening to Iron Creek Bay, and near the openings to the Sorell and Midway Point Causeways). This increase in abundance may be a consequence of the greater upstream penetration of marine waters within the lower estuary (as suggested in the previous section), as nutrient supplies would now be greater to such areas, and conditions would now be generally less stressful. In those locations proximal to areas of constricted water flow, it is possible that tidal currents would be greater, and that nutrient supply would be more regularly supplied.

Throughout the estuary, within the currently muddy areas, abundance has increased greatly. This increase has occurred because of the greater mud content of such areas now than in 1968, and the subsequent effects of nutrient-rich mud in promoting primary production, thereby providing an abundant food source for ostracods. Therefore, as mud has a greater distribution and abundance within the estuary today, the major contrasts between the distribution of abundance between both studies mainly reflects the greatly increased accumulation of mud within the estuary since 1968.

12.5.2.3. Relative abundance of agglutinated and calcareous foraminifera

The distribution of the relative abundance of agglutinated foraminifera in the estuary in 1968 is displayed in Figure 12.17. Calcareous foraminifera were generally more abundant further seaward within the estuary. Within the lower estuary, agglutinated foraminifera were confined to shallower subtidal areas further inland of the estuary mouth, where they had an abundance usually less than 10%. The abundance of agglutinated foraminifera increased further landward, having a maximum abundance of 20% at the head of Iron Creek, and at the western end of Five Mile Beach.

Agglutinated foraminifera were more abundant within the upper estuary, within which they were also more abundant further landward, ranging in abundance from 2.4 to 95%. Generally, agglutinated content was greater in deeper areas further from shore, and lowest (abundance of 2.4 to 7.1%) in the area adjacent to the Midway Point Causeway. Within Barilla Bay, agglutinated content was always less than 50%, and probably ranged from only 14 to 25%.

Within Orielton Lagoon, agglutinated foraminifera ranged from only 2.4 to 20%, appearing to be greater in the deepest of the two sample stations.

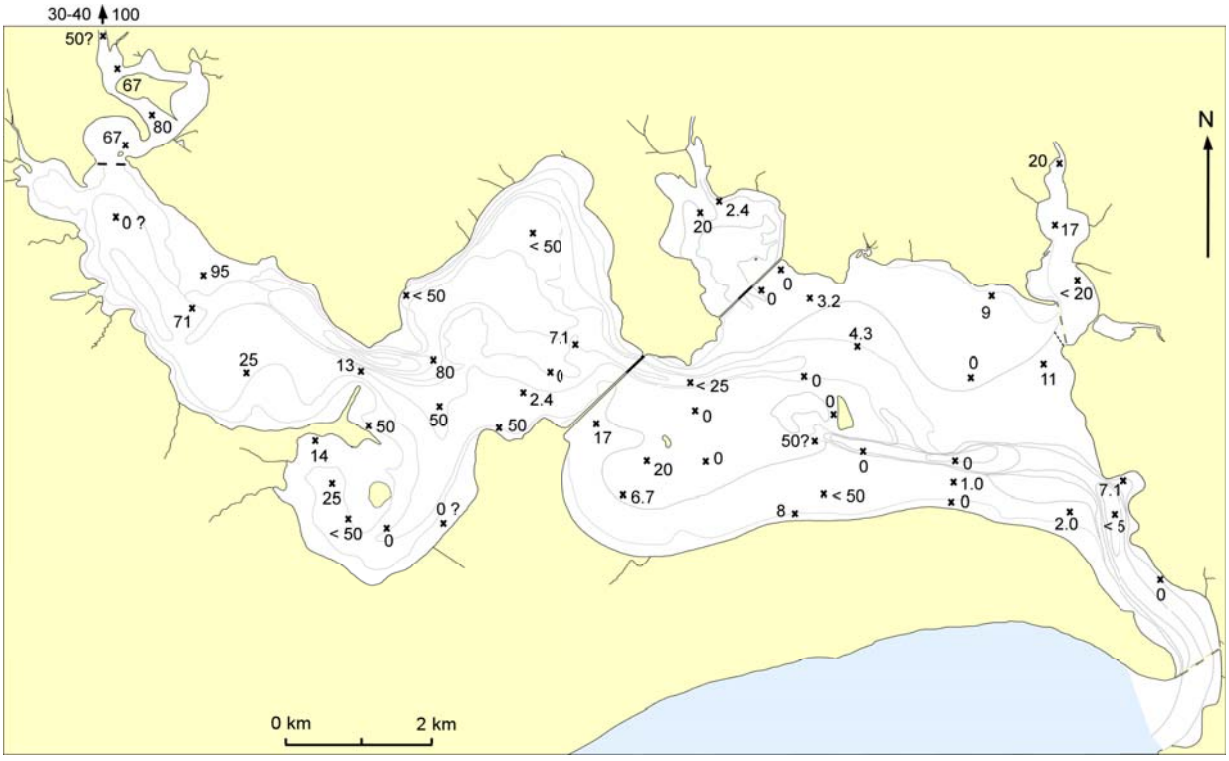

Figure 12.17. Relative abundance of agglutinated foraminifera (Harris, 1968).

By comparing Figures 12.17 and 7.6 it can be seen that agglutinated foraminifera are significantly more abundant within the estuary now than they were in 1968. Within the lower estuary, agglutinated foraminifera are currently more common in all areas, now inhabiting the deeper areas away from the mouth within which they were previously absent. However, the increase in agglutinated content has been greatest within the shallower subtidal depths to which agglutinated foraminifera were confined in 1968, increasing in one location from 3.2 to 97%.

Within the upper estuary, agglutinated foraminifera still increase with increasing water depth, and distance from the shoreline; however, since 1968, agglutinated content has increased in the deeper areas. In the shallower areas, any such changes in agglutinated content are less obvious, although, within Barilla Bay and in the area adjacent to the Midway Point Causeway, agglutinated foraminifera do appear to be more abundant. Within the Coal River, agglutinated foraminiferal content has remained largely unchanged.

The distribution of agglutinated foraminifera within the current estuary has been determined to be largely a result of water stagnation and nutrients creating anoxic conditions, within which pH levels are lowered, such that calcium carbonate dissolution occurs. More stagnant water naturally contains less dissolved oxygen; whereas, nutrient-enriched waters or sediment, promote primary production, leading to oxygen consumption. An increase in the amount of nutrients being supplied to the estuary after the 1960's, was indicated by the short cores as having been mainly responsible for further lowering dissolved oxygen and pH levels within the estuary. The considerable increase in agglutinated foraminifera, and reduction in seagrass distribution, within the lower estuary since 1968 is further indication of such an increase in nutrient supply. In Prestedge (1995), a considerable reduction, after the early 1980's, in seagrass distribution within the lower estuary, was seen to coincide with a general increase in the abundance of algae within shallow waters, which were commonly found growing upon seagrass stems. These observations are indicative of an increase in the nutrients supplied to the lower estuary by surrounding rivers and streams. Water stagnation in areas away from the estuary mouth allows the pooling of waters made increasingly anoxic by algal growth (and decomposition) depleting dissolved oxygen levels. Consequently, large areas of lowered bottom water pH have developed within the lower estuary since 1968.

Additionally, as seagrass contributes oxygen to the waters they inhabit, the loss of significant amounts of such vegetation within the estuary since 1968 may have also promoted the now greater distribution and abundance of agglutinated foraminifera. As the

loss of seagrass has been greatest within the lower estuary, such may have contributed to the greater increase in agglutinated foraminifera in this location.

Increased stagnation may also have contributed to the general increase in agglutinated foraminifera since 1968, particularly within the upper estuary, where water stagnation can effectively reduce bottom water pH. A greater distribution of more stagnant waters could be explained by the decrease in magnitude and frequency of flooding events within the estuary since the construction of the Craigbourne Dam in 1985. Such 'flushing' events would have contributed to generally more mobile water movement in which oxygen levels had less ability to fall to low levels.

Consequently, the increase in nutrients supplied by fluvial waters to the lower estuary has increased greatly, such that oxygen and pH levels within the shallow subtidal areas of quieter water within the lower estuary (in which agglutinated foraminifera were confined to low amounts in 1968), have fallen to such levels that calcareous foraminifera are now subject to severe dissolution, and agglutinated foraminifera are now dominant. Similarly, within the subtidal waters of the upper estuary, dissolved oxygen content is now less than it was in 1968; however, the increase in abundance of agglutinated foraminifera is less obvious, as the reduction in tidal exchange imposed by the Midway Point causeway meant that the waters were originally fairly stagnant.

12.5.2.4. Ratio of Ostracoda to foraminifera

In the 1968 study, foraminifera were typically more abundant than ostracods, with the exception of shallow subtidal areas away from the mouth (Figure 12.18). The relative abundance of Ostracoda to foraminifera was least within the inlet channel, within which current strength was too high for Ostracoda to inhabit.

In the current study, foraminifera are also generally more common than ostracods, yet only with the exception of two shallow subtidal areas away from the mouth within the lower estuary (Figure 12.19). The ratio of Ostracoda to foraminifera is very low in the deeper muddier areas of the upper estuary and Orielton Lagoon, and within the inlet channel.

By comparing Figures 12.18 and 12.19, it can be seen that since 1968 the abundance of Ostracoda relative to foraminifera appears to have decreased generally dramatically. This change has been greatest within the upper estuary, and is probably due to the greater distribution, since 1968, of lower pH waters (caused both by an increase in nutrients dissolved in water, or attached to sediment), as ostracods are less tolerant of the low

dissolved oxygen, low pH, and high turbidity of such waters. Consequently, areas of shallow subtidal clean sand, within which ostracods are typically more abundant than foraminifera, are now restricted to the lower estuary, due to the disappearance of such areas from the upper estuary since 1968.

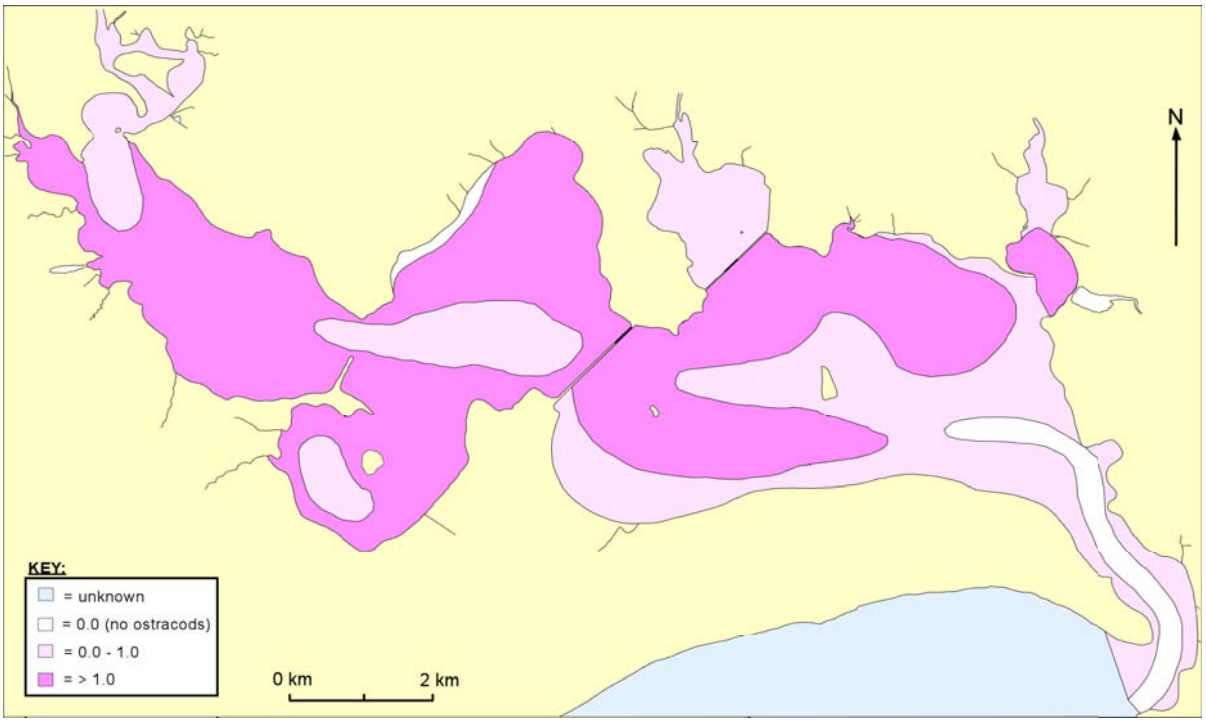

Figure 12.18. Ratio of ostracod to foraminiferal abundance (Harris, 1968).

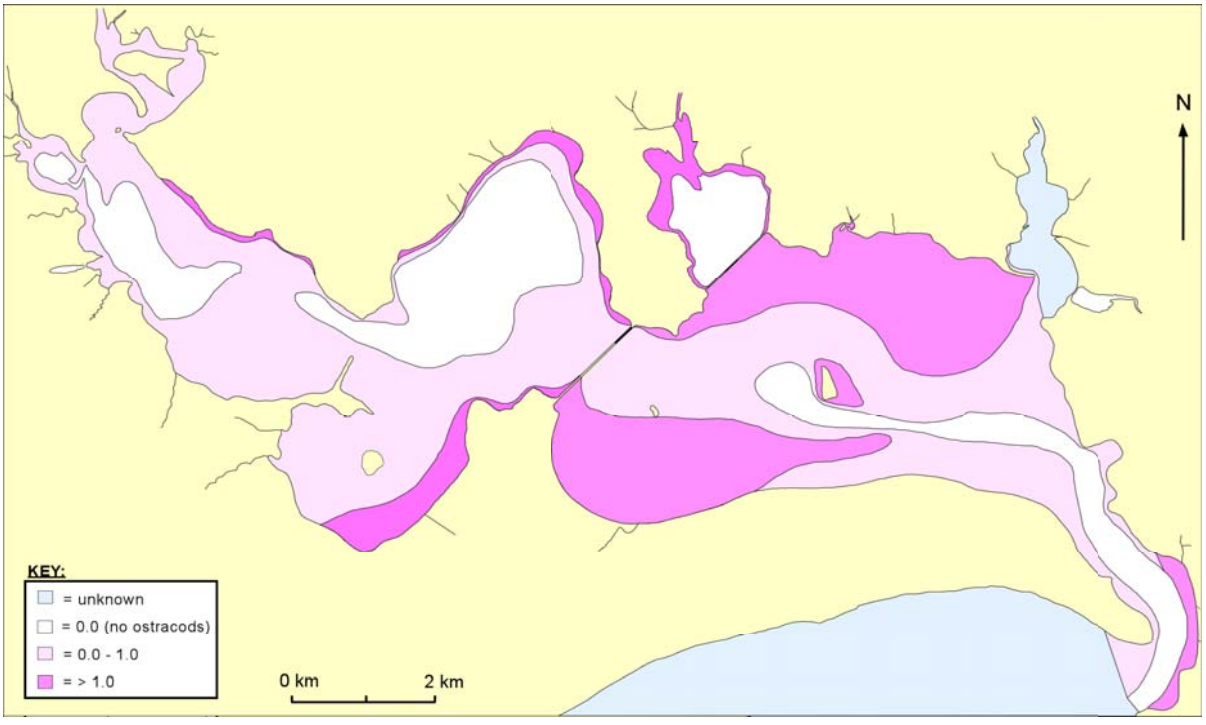

Figure 12.19. Ratio of ostracod to foraminiferal abundance in current study.

12.5.2.5. Foraminiferal species

(i) *Elphidium incertum*

Elphidium incertum was the most abundant and widespread species found throughout the estuary in 1968. According to Figure 12.20, the species was 'abundant to plentiful' at the heads of the Orielton Rivulet, Iron Creek, and the Coal River, as well as 'abundant' within the estuary mouth. The species was also 'common to plentiful' at the opening of the Coal River into the estuary, in the shallower areas of the upper estuary, and in various locations of the lower estuary west of Woody Island.

From analysis of plates from Phleger (1960), it is probable that Harris' *E.incertum* was the most likely equivalent to a range of *Elphidium* species found in the estuary today, but may mostly comprise the ecophenotypes of *Elphidium excavatum* (i.e. *excavatum, clavatum, williamsoni*). The abundance of *E. incertum* within the estuary mouth probably correlates with the concentration of *E. excavatum williamsoni* within the estuary mouth today. The furthest upstream concentrations of the species are likely to correlate with the distribution of *E. excavatum excavatum*; whereas, intermediate concentrations of *E. incertum* probably correlate with *E. excavatum clavatum*.

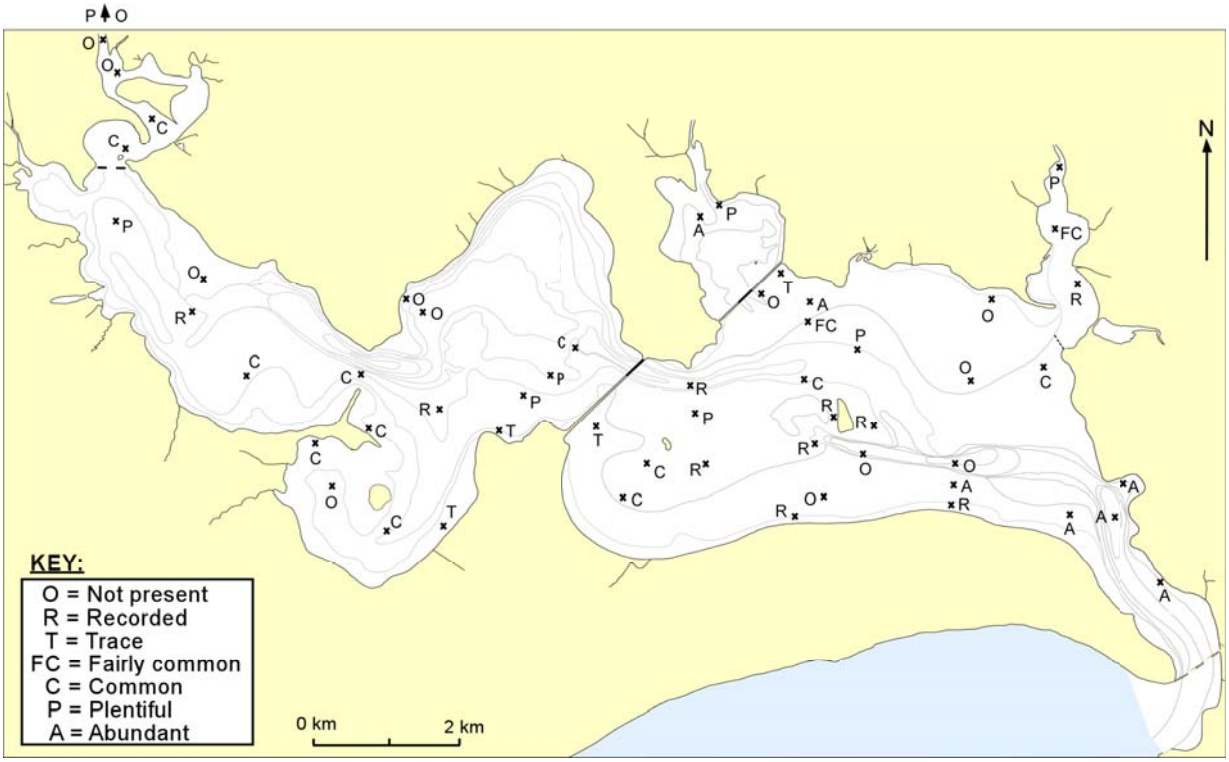

Figure 12.20. Distribution of *Elphidium incertum* (Harris, 1968).

It is difficult to draw conclusions on how the distribution of *'E. incertum'* has changed since 1968, due to the range of species it may represent and the overlapping distributions

of these species; however, from examining at the distribution of the genus *Elphidium* within the estuary today (Figure 12.21) the presence or absence of the genus in certain areas in 1968 can be determined. Additionally, the distribution of *'E. crispum'* and *'E. macellum'* in the 1968 study coincides with that of *'E. incertum'*.

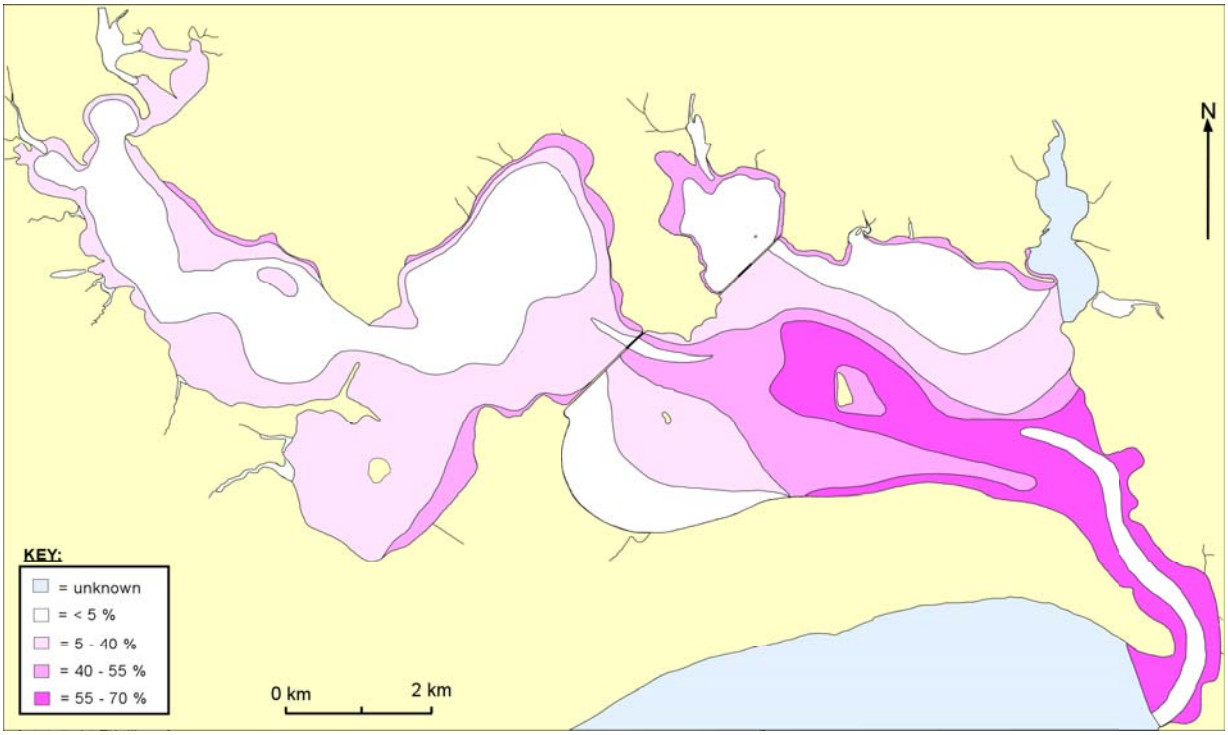

Figure 12.21. Relative abundance (%) of the genus *Elphidium* in the current study.

Within the lower estuary, *E. incertum* is generally absent from those very shallow subtidal areas away from the mouth, from which species of *Elphidium* are nearly absent today. However, within the upper estuary, the genus was absent from the deeper areas in the current study, as well as in the 1968 study, but is less abundant now within the lowermost reaches of the Coal River where it opens into the estuary. The most likely equivalent *Elphidium* species in the Coal River, *E. excavatum excavatum*, is the *Elphidium* most tolerant of lower salinity conditions, so its reduced downstream distribution within the Coal River today would imply that the influence of river flow upon faunal composition has been reduced, probably due to a reduction in flooding events. A reduction in pH levels is not likely to have caused this change in *Elphidium* distribution, as lower pH levels would be expected to occur further upstream where fluvial (low pH) water influence is greater. Additionally, the 1968 study was completed after a very dry season, implying that even during such a period of highly reduced river flow, freshwater influence upon the fauna was still greater than it is today.

(ii) *Ammonia beccarii*

Ammonia beccarii was described by Harris (1968) as being characteristic of shallow water muddy sands within the estuary. It was most abundant within, and at the opening into the estuary of, Iron Creek, Orielton Rivulet, Barilla Rivulet and Coal River (Figure 12.22). It was generally absent or rare in other areas of the estuary, apart from shallow waters in Midway Bay and immediately west of the Midway Point Causeway.

Ammonia beccarii is considered here to be equivalent to *Ammonia aoteana* of the current study. Within the Coal River, the species has a slightly greater downstream extent than it does in the current study, as does *E. excavatum excavatum*, implying again that freshwater influence has decreased to some degree within the upstream area of the upper estuary (Figure 12.23). The absence of the species within the deeper areas of the upper estuary is still prevalent in the current study, suggesting that shallower water conditions are still preferred.

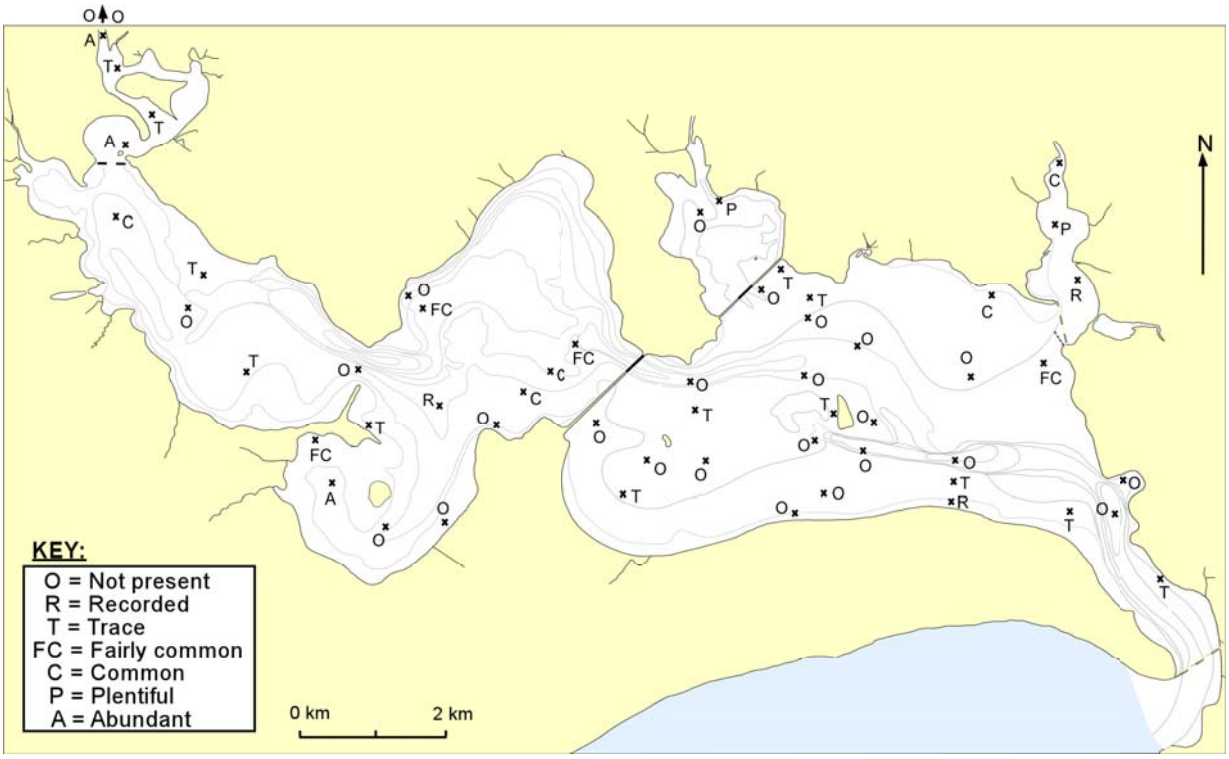

Figure 12.22. Distribution of *Ammonia beccarii* (Harris, 1968).

Areas of maximum abundance of *A. beccarii* within the lower estuary and Orielton Lagoon appear to be largely unchanged since 1968. The absence of the species in much of the lower estuary in 1968, may actually be a consequence of the small number of

foraminifera counted in many areas of that study, as the species only occurs in low amounts generally today.

Figure 12.23. Distribution of *Ammonia aoteana* in current study.

(iii) *Miliammina arenaea*

M. arenaea was described by Harris (1968) as being the most prevalent agglutinated species within the estuary at that time. The species was most common within the mouth of Iron Creek, Orielton Rivulet, Barilla Rivulet, and Coal River, and largely absent from most areas of the estuary, except for small amounts within the lower estuary in shallower waters away from the mouth (Figure 12.24).

M. fucsa of the current study is considered here to be a modern equivalent to *M. arenaea* of the earlier study. The species is still most abundant within the mouths of rivers/streams which enter the estuary, as it was in 1968, preferring muddy sediments, and more freshwater influenced locations (Figure 12.25). However, it is less abundant now in the shallow subtidal waters upon the secondary lobe downstream of the Coal River, suggesting again that the downstream extent of freshwater influence has become more reduced. The species also appears to be much more abundant within the deeper areas of the upper estuary today, although the lack of a sufficient number of samples from such locations in the 1968 study, makes it difficult to confirm this possible change.

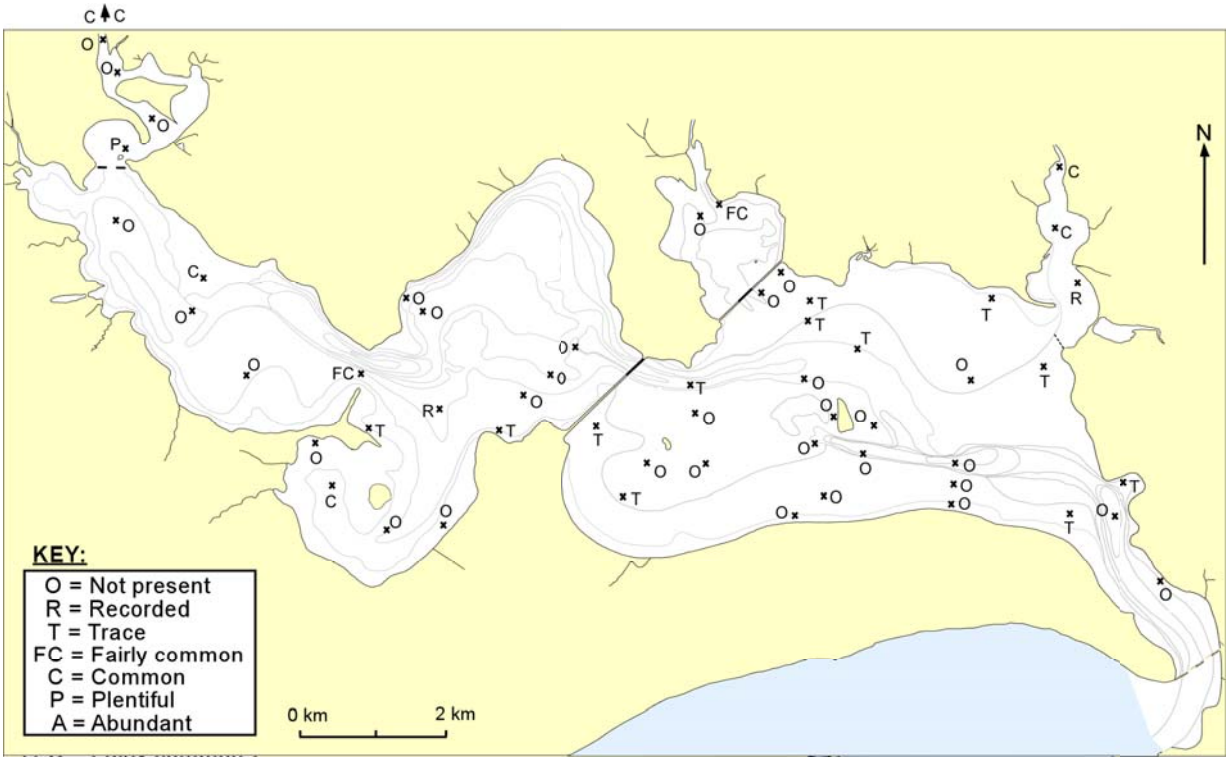

Figure 12.24. Distribution of *M.arenaea* (Harris, 1968).

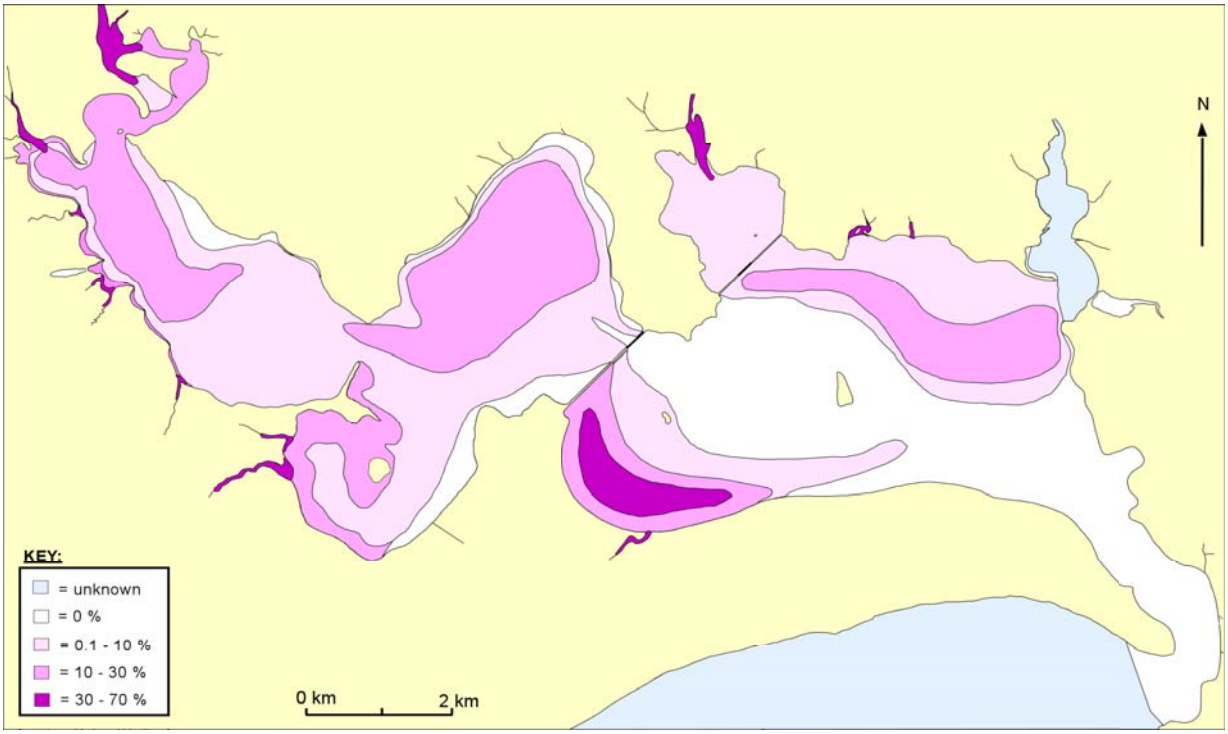

Figure 12.25. Distribution of *M. fucsa* in current study.

Within the lower estuary, the species now has a significantly greater abundance within the shallow waters away from the mouth. Within this area, agglutinated content now is (as described earlier) much more abundant. Although the species occurred in very low amounts there in 1968, it has now developed in numbers greatly due to the reduction in pH and increase in nutrient supply in these areas.

Therefore, the increase in abundance of the species in some areas of the estuary is a consequence of the increased nutrients supplied to the estuary; whereas, its possible reduction in abundance at the mouth of the Coal River may be a result of reduced freshwater influence in that area.

(iv) *Ammobaculites* sp., *Haplophragmoides canariensis*

Figure 12.26 displays the distribution of both *Ammobaculites sp.* and *Haplophragmoides canariensis* from Harris (1968). Generally both species occurred in the same localities, suggesting that the latter species may actually represent broken, early coiled portions of the former species. Generally, the two species had a minor distribution within the estuary, inhabiting shallower subtidal waters, within the upper estuary, and away from the mouth in the lower estuary. The two species were, however, common within Coal River.

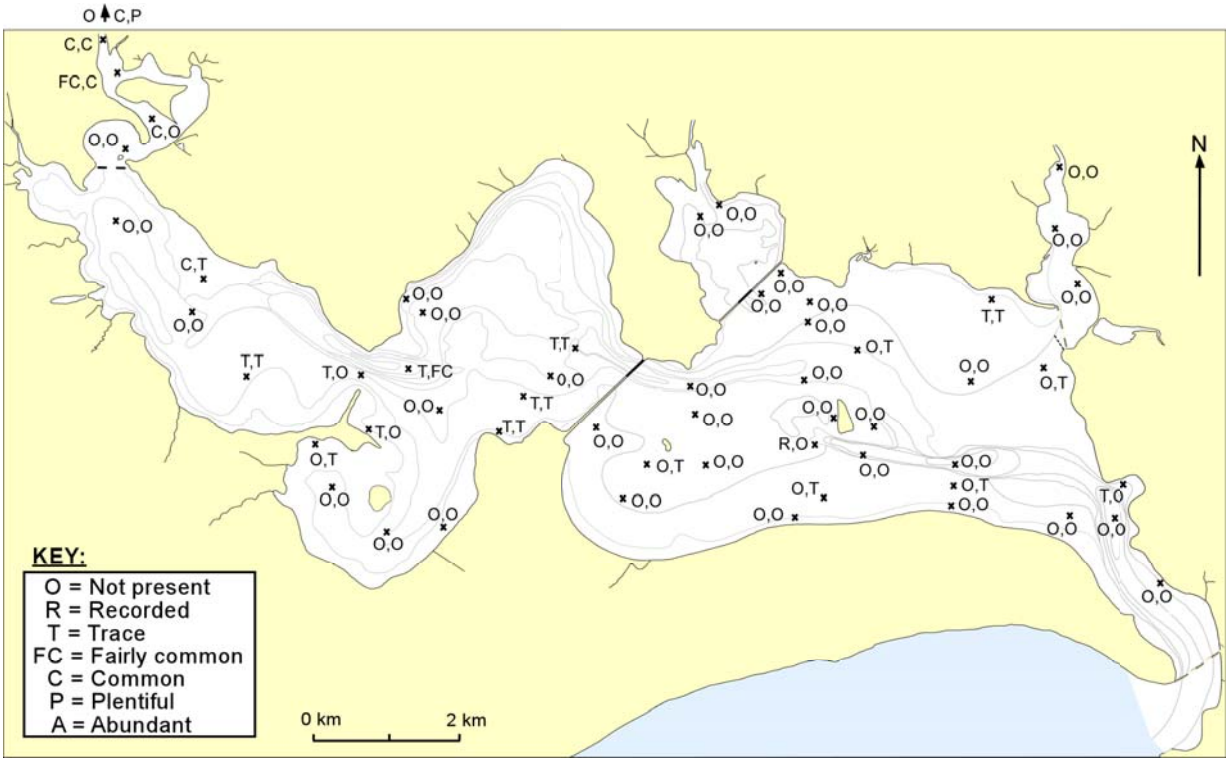

Figure 12.26. Distribution of *Ammobaculites* sp. (1,0) and *Haplophragmoides canariensis* (0,1) (Harris, 1968).

It is considered here, that *Ammobaculites barwonensis* of the current study is actually a modern equivalent of both *Ammobaculites sp*. and *H. canariensis* from the 1968 study. The species has remained abundant within the Coal River, yet the minor presence of the species within the rest of estuary in 1968 has greatly increased since then, so that it is currently the most abundant species in the estuary. This is a consequence of the general increase in nutrients supplied to the estuary since 1968, which has lead to a general decrease in pH levels throughout the estuary, enabling the species to increase greatly in abundance and distribution.

The greater abundance of *Ammobaculites barwonensis* relative to *Miliammina fusca* in the current study, shows that *A. barwonensis* is more successful than *M. fucsa* in the estuary today, than it was in 1968.

(v) *Miliollinella subrotunda and Quinquelocilina simplex*

In the 1968 study, *Miliollinella subrotunda* was the most abundant porcellaneous species within the estuary. Its distribution in 1968 (see Figure 12.27) shows that the species was rarely present in the upper estuary, and was most abundant within the lower estuary, particularly at shallower subtidal depths, within the inlet channel, and within the mouth of Iron Creek.

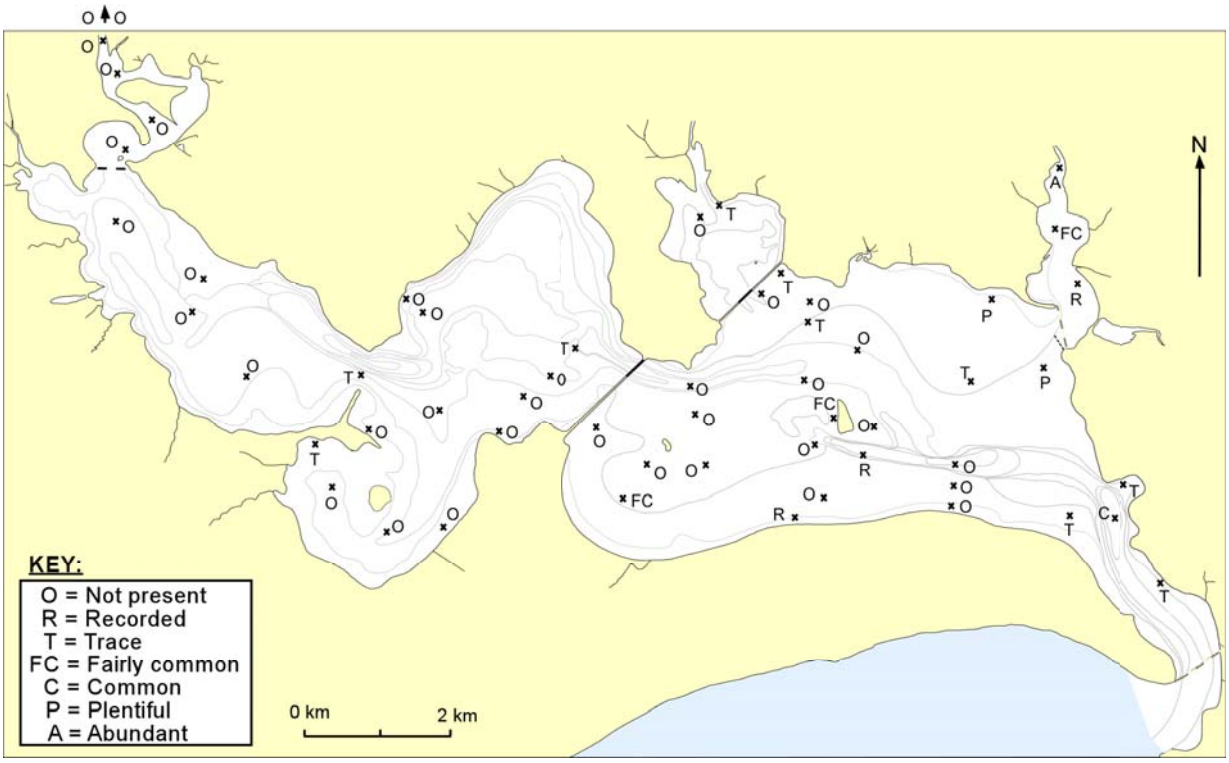

Figure 12.27. Distribution of *Miliollinella subrotunda* (Harris, 1968).

Species of *Miliollinella* identified in the current study *(M. lakemacquariensis, M. circularis, and M. pyrgoformis)* also occurred (in very low numbers) only within the lower estuary. These species occurred in only four samples, located within the inlet channel and adjacent to the opening of the Sorell Causeway. Therefore, the distribution and abundance of the genus appears to have reduced greatly since 1968, and is now mainly confined to higher energy marginal marine environments. This may suggest that the genus still prefers marine influenced areas within the estuary, yet it cannot tolerate the low pH levels within the shallow subtidal zone of the lower estuary, and subsequent effects of dissolution.

Q. simplex was the second most abundant porcellaneous species of the estuary in the 1968 study of the estuary. Its distribution (shown in Figure 12.28) shows that the species, like *M. subrotunda*, prefers shallow subtidal areas, mainly within the lower estuary. As it is not known what the species may be equivalent to, taxonomically, within the current study, it can only be noted that species of *Quinqueloculina* in the current study are rare or absent from many of the areas in which *Q. simplex* was distributed in the 1968 study. This suggests that the lower pH levels in these shallower subtidal waters are now too low to have allowed the species to continue inhabiting these areas some time since the earlier study.

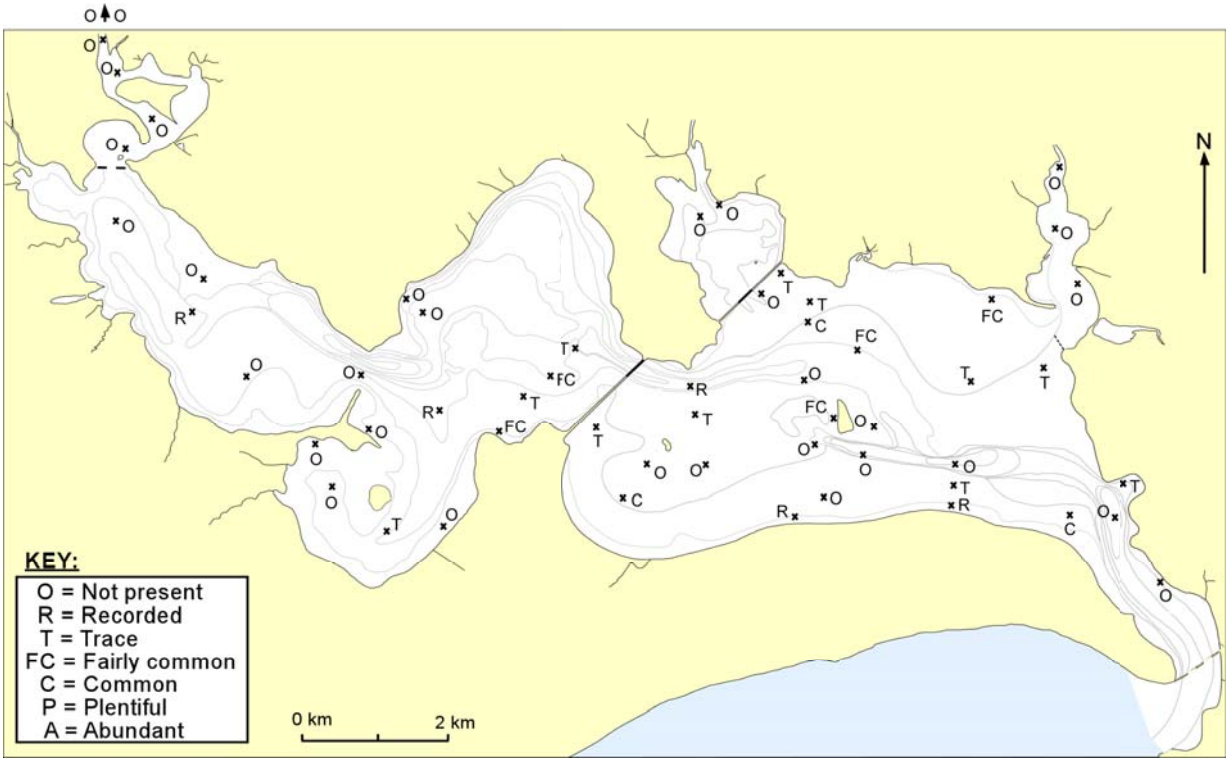

Figure 12.28. Distribution of *Quinqueloculina simplex* (Harris, 1968).

(vi) Other minor species

The distribution of *Trochammina inflata* has changed little since the 1968 study. In the earlier study, the species was described by Harris (1968) as being restricted to higher tidal flats. Similarly, in the current study, the species is most abundant within the intertidal zone.

The current distribution of *Guttulina regina* is also similar to the 1968 distribution of the species, occurring in both studies in similar locations within the estuary mouth.

Cibicides sp. was only a very minor species identified within the estuary in the 1968 study, having been found at only three locations within, or slightly adjacent to, the inlet channel. It is likely that *Cibicides refulgens* of the current study is a modern taxonomic equivalent of *Cibicides sp.* from the earlier study. *C. refulgens* is similarly restricted to the mouth of the estuary, although its greater abundance and landward extent in the current study suggests that marine waters reach further upstream within the lower estuary today.

Bulimina marginata was identified in both the current study and 1968 study. In the current study, the species occupied the marine-influenced area of the lower estuary, covering an area ranging from the outermost sample station of the estuary mouth up to the Midway Point Causeway. In contrast, the species has a very limited distribution within the estuary in the 1968, occurring in only two locations within the estuary mouth. As with *Cibicides sp.*, the 1968 distribution of *B. marginata* suggests that marine waters reach further upstream within the lower estuary today.

In the earlier study, the species, *Reophax cureta*, was a minor species occurring throughout the estuary. It is likely that this species of the genus *Reophax* is equivalent to *Cuneata arctica* in the modern study, as the latter species has been previously been placed within the genus *Reophax*, and both species were the only agglutinated, uniserial forms identified in both studies. In the earlier study, *R. cureta* had a scattered distribution, and occurred mainly within the lower estuary; whereas, in the current study, *C. arctica* was most abundant in deeper muddier areas of the upper estuary. It is not known what may have caused this switch in the distribution of the species between the Upper and lower estuary since 1968.

12.5.2.6. Ostracod species

(i) *Loxoconcha* sp.

Figure 12.29 displays the distribution of *Loxoconcha* sp. in the study of Harris (1968). The species mainly occurred in intertidal to shallow subtidal depths proximal to stream/river outputs, as well as within river channels/mouths.

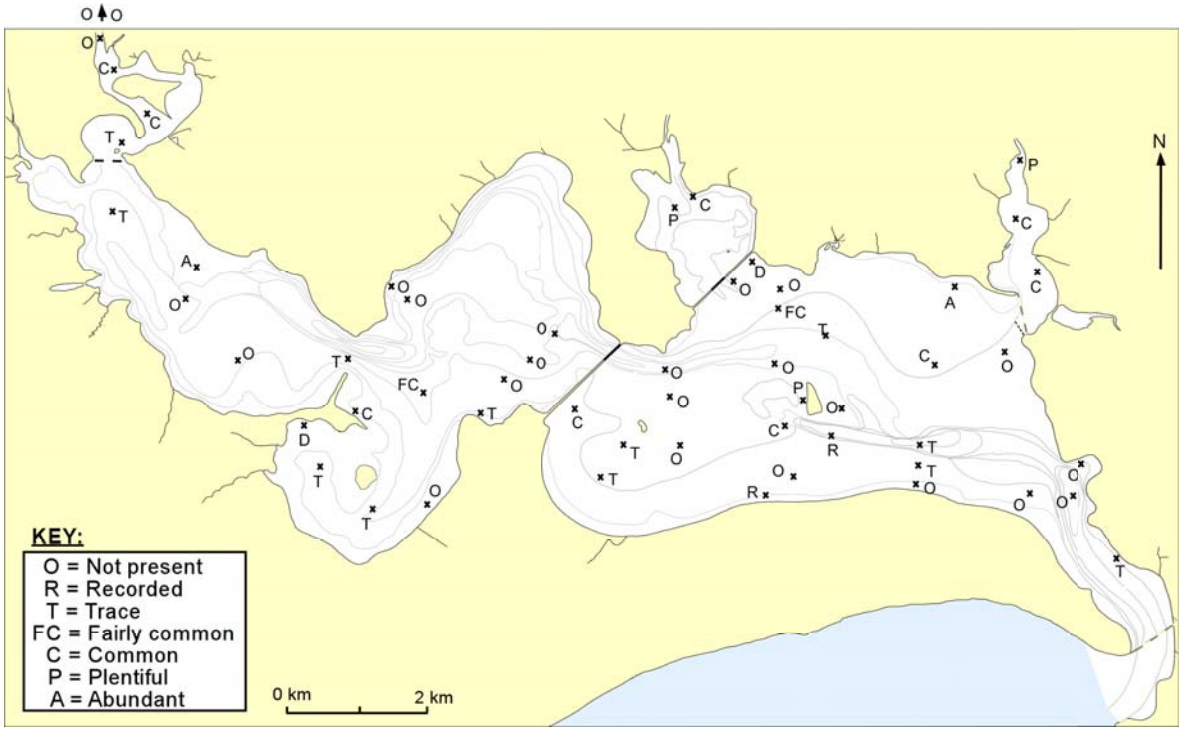

Figure 12.29. Distribution of *Loxoconcha* sp. (Harris, 1968).

In the current study, the most common species of *Loxoconcha*, *L. australis*, is restricted to deeper subtidal environments within the Lower and upper estuary, being more common in the deepest, muddier sediments of the lower estuary, and most abundant within the channel environments of sample #60, and the Midway Point causeway (Figure 12.30).

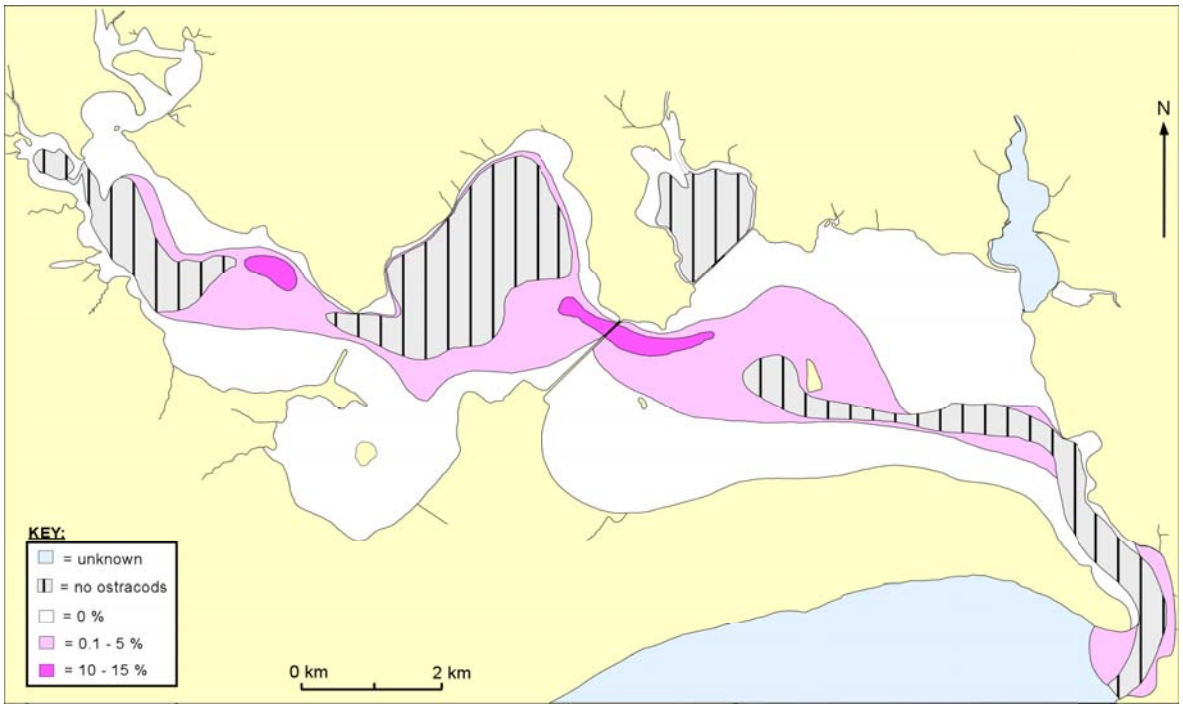

Figure 12.30. Relative distribution of *L. australis* (%) in current study.

As the distributions of *Loxoconcha* sp. and *L. australis* are very different, with the former species preferring shallower depths, and the latter species preferring deeper depths, it is likely that these species are not equivalent. This suggests that either *Loxoconcha* sp. is no longer present within the estuary, or that it was actually misidentified. In fact, the distribution of *Loxoconcha* sp. is more similar to that of *L. hartmanni* of the current study.

(ii) *Microcythere* sp.

Figure 12.31 displays the distribution of *Microcythere* sp. in the study of Harris (1968). The species was relatively rare, occurring at intertidal and deeper subtidal depths. The three species belonging to *Microcytherura* in the current study (*M. australis, M. hornibrooki, M. triebeli*) represent a significant proportion of ostracod specimens within the estuary. In the current study, these species are more abundant within the lower estuary than the upper estuary, and prefer normal marine salinity, although *M. hornibrooki* can tolerate considerable variation in salinity.

The highly contrasting distribution and abundance of *Microcythere* sp. and species of *Microcytherura* suggest that either *Microcythere* sp. is actually a different species to any of the species of *Microcytherura* in the current study, or that the latter species were all rare within the earlier study. The latter option would suggest that normal marine salinity conditions were less prevalent in the estuary in 1968 than they are now.

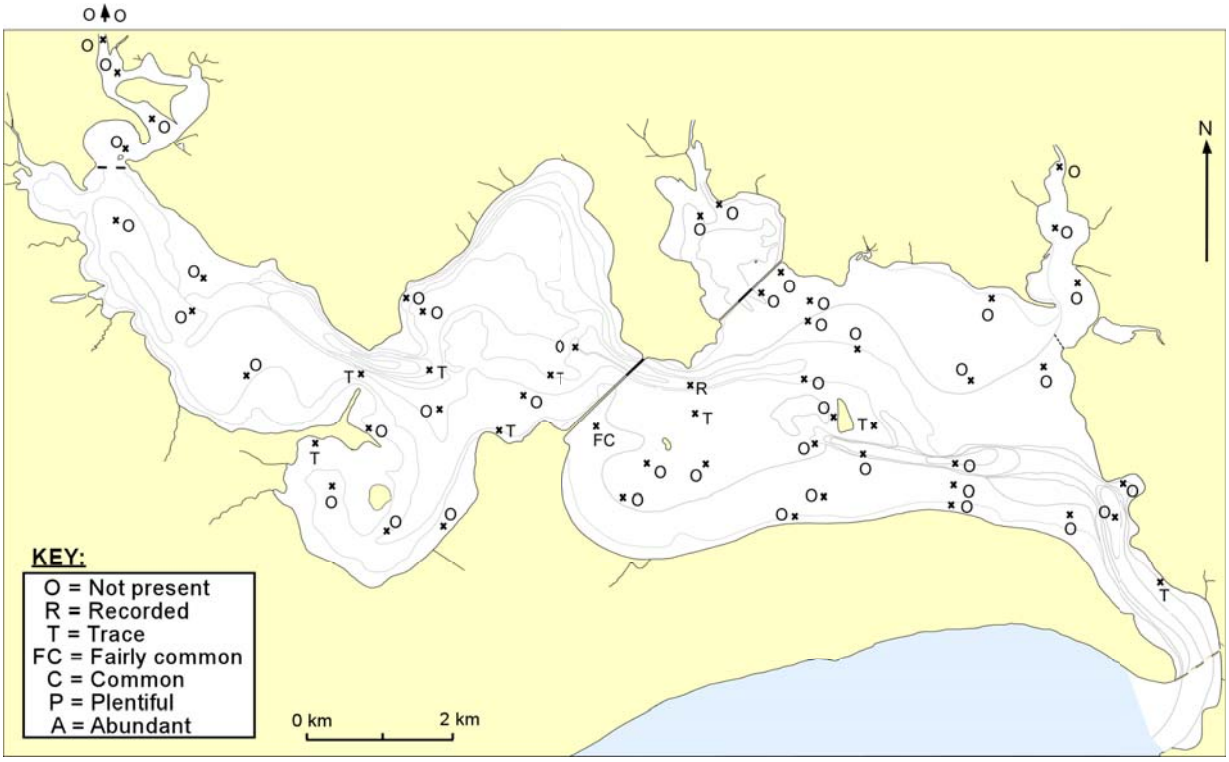

Figure 12.31. Distribution of *Microcythere* sp. (Harris, 1968).

12.6. Summary and conclusions

Comparison between the sediments and geomorphology of the Pitt Water Estuary from 1968 and 2001 indicate that during the intervening period mud has increased in distribution and abundance within the estuary, while sand transport appears to have remained in a state of equilibrium. This increase in mud accumulation is likely to be a result of the increase in suspended sediment supplied by runoff from the catchment area due to increased agricultural land use since 1968.

In 1968, mud was mainly confined to the upper estuary, Orielton Lagoon, and the fluvial deltas and intertidal areas of seagrass in the lower estuary. These areas of seagrass have since disappeared, and mud is now absent from the intertidal zone of the lower estuary except in fluvial deltas; however, mud now has a wider distribution within the basinal area between the causeways and Woody Island.

Mud content was grossly underestimated in Harris (1968) for the deeper areas of the upper estuary, as it is in direct contrast to mud content measured in the 1968 layer of the Midway Bay core. This means that it cannot be confirmed if mud is more abundant within the deeper areas of the upper estuary. However, the loss of segrassed areas has removed some previous sites of maximum mud accumulation in the upper estuary.

The distribution and abundance of benthic foraminifera and Ostracoda within the estuary has changed significantly since 1968. These changes include: a general increase in species diversity (particularly in the lower estuary); a slight increase in abundance within the clean sands of the lower estuary; a significant increase in abundance in now muddy areas; a significant increase in the abundance and distribution of agglutinated foraminifera; and changes in the downstream or upstream extent of distribution of certain species.

The significant increase in nutrients supplied to the estuary since 1968 mainly accounts for the increase in distribution of agglutinated foraminifera since then. The increase in primary production (particularly by algal growth) caused by increased nutrients lead to dissolved oxygen depletion, and subsequent pH reduction, within areas of stagnant water within the estuary. The increase in agglutinated foraminifera appears to have been greatest within the lower estuary, indicating that considerable areas of water there have become oxygen depleted. Additionally, as seagrass contributes oxygen to the waters they inhabit, the loss of significant amounts of such vegetation within the estuary since 1968 may have also promoted the now greater distribution and abundance of agglutinated foraminifera. Furthermore, a general increase in water stagnation within the estuary following construction of the Craigbourne Dam in 1985, may have contributed to depleted dissolved oxygen within areas of the estuary, particularly in the upper estuary.

A reduction in the downstream extent of Coal River flooding (and therefore, of freshwater influence upon faunal composition) has lead to an increase in species diversity, and greater landward distribution of marine species, within the lower estuary by allowing greater upstream penetration by marine waters. Also, the downstream extent within the Coal River of certain calcareous species may have been decreased due to the reduction in Coal River flooding.

In those areas of the estuary where mud now has a greater distribution and abundance, there has been a significant increase in faunal abundance as a result of the higher nutrient conditions of muddy sediments promoting greater primary productivity, thereby providing a greater food supply for benthic fauna. However, this has also lead to a decrease in the ratio of Ostracoda to foraminifera, as ostracods are less tolerant of the lowered pH conditions which tend to occur in muddier areas of the estuary.

A slight increase in species diversity within Orielton Lagoon since 1968, may have occurred due to the lowering of the culverts of Sorell Causeway in 1993, with the subsequently increased tidal exchange having reduced environmental stress.

CHAPTER 13. RECENT SEAFLOOR ENVIRONMENTS - DISCUSSION

13.1. Recent change in seafloor environments of the estuary

13.1.1. Development of benthic fauna habitat zones

During the 20th century there has been substantial change in the distribution of benthic fauna zones within the estuary. In chapter 11, short core information allowed such change to be described at specific locations within the upper estuary. In this section, the changes in benthic fauna zones throughout the upper estuary since the 1940's are summarised briefly, as they provide much of the basis for description of changes in environmental factors described in the next section.

The development of foraminiferal associations over time, interpreted from short core information, provides the most useful illustration of the change which has occurred in environmental conditions upon the seafloor of the upper estuary during the 20th century. Figure 13.1 provides a summary of the change in foraminiferal associations within the upper estuary between the 1940's and 2002. During the 1940's (and probably earlier) pH levels were at their highest for the 20th century, with dense shell layers present in most shallow water areas. Foraminiferal associations Ab, AaAb, and Aa(Ab) were likely to be the only associations present within the upper estuary. The distribution of the two main species of the associations, *A. aoteana* and *A. barwonensis*, varied with water depth, with *A. aoteana* (dominant species of Aa(Ab)) more common in shallower, high pH waters, and *A. barwonensis* (dominant species in Ab) being present in deeper, lower pH waters.

Figure 13.1 shows how associations AaAb and Aa(Ab) were replaced by newer associations within the upper estuary after the 1940's, and how the distribution of association Ab has changed. These developments have been the result (as will be described in the next section) of generally decreasing pH levels, and increasing nutrients within muddy sediments. During the 1950's, the higher amount of nutrients within sandy muds of association Ab lead to increased abundance of *C. arctica*, *M. fucsa*, and *T. earlandi* relative to *A. barwonensis*, such that association C replaced Ab in the deeper areas. The *Elphidium excavatum* ecophenotypes (*excavatum* and *clavatum*) coped better with the general decrease in pH within the upper estuary since the 1940's, such that they gradually replaced *A. aoteana* as the dominant calcareous foraminiferal species, with associations AbEc, Ec,

and AbEe appearing. In more upstream areas, lower pH waters and more nutrient-enriched sediments, lead to increased abundance of *M. fucsa*, with the emergence of association M.

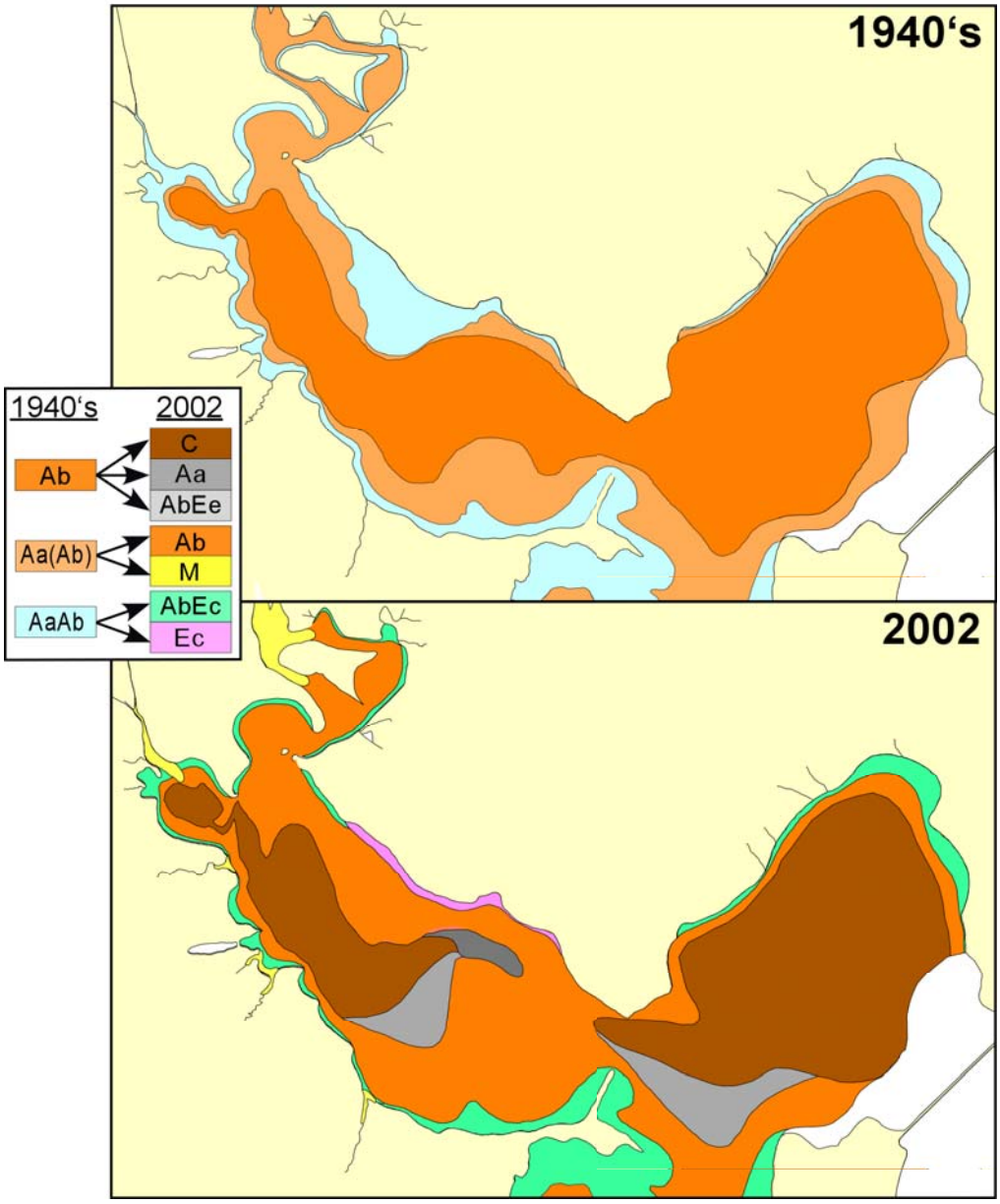

Figure 13.1. Distribution of foraminiferal associations within the upper estuary during the 1940's & in 2002 (with the development of associations indicated).

The short cores indicate that ostracod associations Mp, Mh and LhPs were present within the upper estuary during the 1940's. These associations are still present within the upper estuary today. Compared to foraminifera, much less information could be drawn from the short cores on how the distribution of the ostracod associations developed within the upper estuary since the 1940's; however, it appears that association Mh was not restricted to intertidal depths as it is today, but was present at shallow subtidal depths as a result of the generally higher pH conditions. Additionally, generally lower water turbidity in the upper

estuary during the 1940's probably allowed the association to spread into deeper water, as the dominant species of the association, *M. hornibrooki*, appears to prefer more illuminated waters within the modern estuary. During the 1940's, as today, ostracods were absent from the deep, sandy muds of the upper estuary, due to very low pH, and association Mp was present at shallower subtidal depths.

13.1.2. Development of the distribution and value of environmental factors

A relatively small number of environmental factors have been involved in the alteration of seafloor environments within the estuary during the 20th century, the most important of which is bottom water pH. In this section, the change with time in the distribution and value of these factors is described. The specific causes behind these changes will be described in the subsequent section.

13.1.2.1. Bottom water pH and dissolved nutrients

During the 20th century, bottom water pH has changed significantly within the Pitt Water Estuary. At the beginning of the century, pH was high within the lower estuary, but was considerably lower within the upper estuary. As the short cores were not dated back to a period before the Midway Bay causeway was built, it is uncertain how low pH was within the upper estuary before the causeway existed; however, the sharp contrast (both today and earlier in the 20th century) in pH between the upper and lower estuary indicates the causeway contributed to lowering pH within the upper estuary.

Figure 13.2 displays a suggested reconstruction of changing pH conditions within the upper estuary since the 1940's. It is based mainly upon short core data, with evidence of the effects of increasing calcite dissolution used as a primary index for decreasing pH over various time periods. Consequently, the ratio of agglutinated to calcareous foraminifera was used mainly, in addition to the clam and oyster content of sediments, and the abundance of ostracods. The Samphire Island core was used mainly as an indicator of conditions at shallow subtidal depths within the Coal River, with the Duckhole Rivulet core used for shallow water locations further downstream, and the Midway Bay core used to describe deeper water locations. The ratio of agglutinated to calcareous foraminifera in Harris (1968) was also used to assist in describing pH changes since 1968.

The 1940's were used as the first stage of the pH reconstruction, as it was the time period when the clam shell layer in the Samphire Island core was probably present, as well as part of the actual time period (1920's to 1970's) in which an oyster bed (consisting of *Ostrea*

angasi) was present within the Duckhole Rivulet core. Agglutinated foraminiferal content within the clam and oyster layers was low to moderate, and ostracod content high, indicating that pH ranged from high to intermediate at shallow depths. The clam shell layer of the Samphire Island core consisted mainly of *Notospisula trigonella*, but also contained less gastropods. Such clam shell layers were probably widespread in the shallower waters of the upper estuary at that time due to the general higher pH conditions. The actual distribution of oyster beds at the time within the upper estuary is unknown, but oysters beds were likely to have been common at least within the shallow waters of the mouth of Duckhole Rivulet.

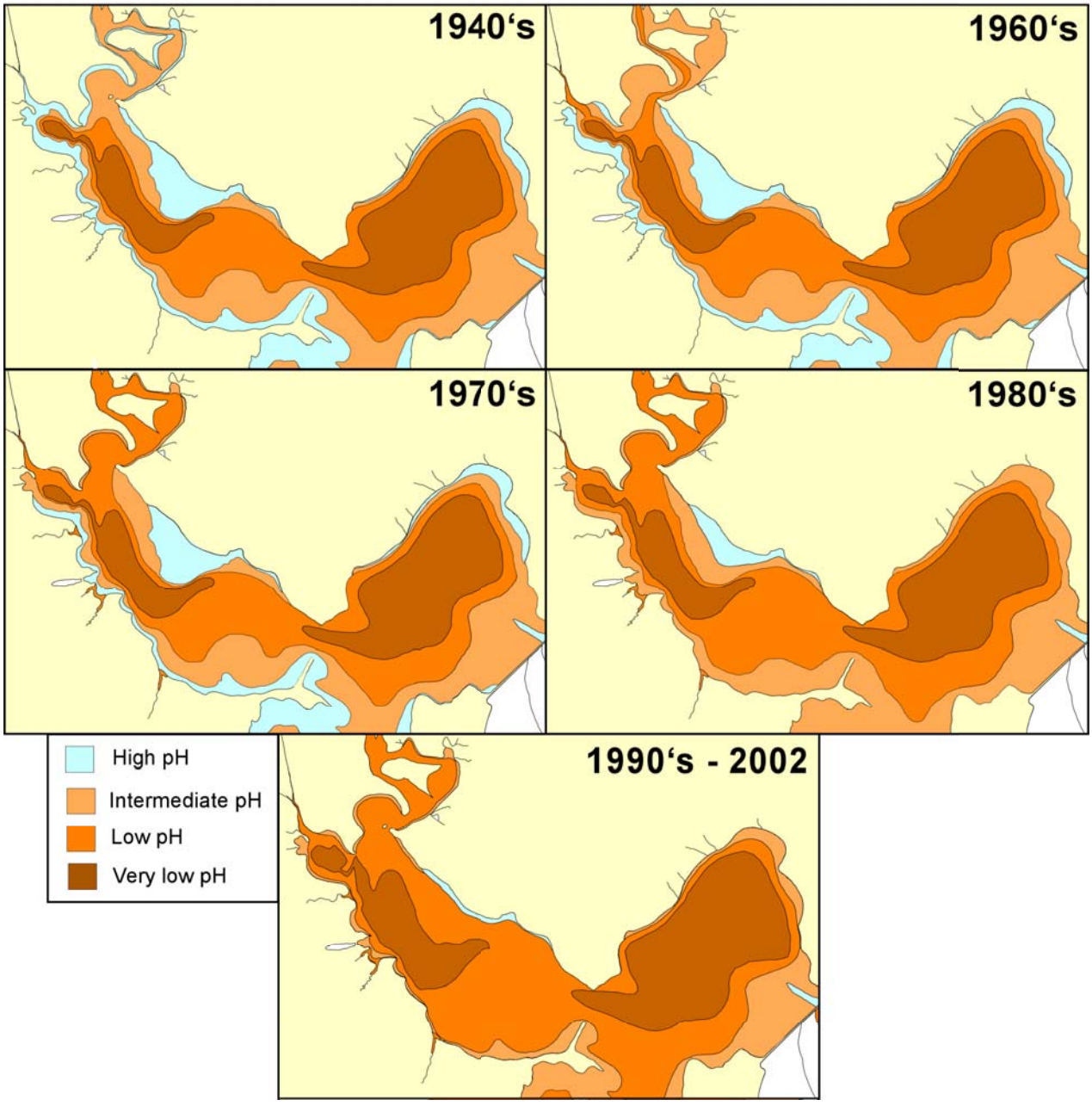

Figure 13.2. Suggested pH distribution within the upper estuary at various stages of the 20th century.

During the 1940's, within the upper estuary, pH was only related to water stagnation, with pH decreasing in deeper, more stagnant water further offshore, due to more anoxic water conditions. High pH was confined to intertidal depths and areas of seagrass, with intermediate pH in rivers, streams and shallow subtidal waters, with shell layers present in such environments. Low pH, in which shell layers were absent, occurred only in deeper subtidal waters, with very low pH (causing severe calcite dissolution) occurring in the deepest waters. Consequently, with increasing depth agglutinated foraminifera were more abundant.

During the 1960's, a lowering in pH occurred within the rivers and streams of the upper estuary. Fertiliser nutrients and dissolved organic matter (DOM) delivered by fluvial waters, derived from runoff from agricultural lands, lead to deeper areas of low pH water within the Coal River (and probably also in other rivers/streams), which may have linked with the low pH waters within the main body of the upper estuary. Within affected rivers, shallower subtidal and intertidal waters had intermediate pH, with high pH intertidal waters disappearing. Within the Coal River, this meant the end of clam growth and shell accumulation, a severe reduction in ostracod abundance, and a significant increase in agglutinated foraminifera. Although the oyster bed was still present within the mouth of the Duckhole Rivulet, foraminifera within the bed indicate a slight lowering of pH levels during this period. Additionally, within the deep water sediments of Midway Bay, foraminiferal abundance increased steeply, indicating that the nutrient content of sediments was increasing. This indicates that pH was probably also decreasing slightly within such areas during the 1960's. Consequently, the lowering of pH occurred mainly within various rivers and streams which were now carrying waters with increased DOM content and fertiliser nutrients; however, a slight decrease also occurred generally within the rest of the upper estuary.

During the 1970's, the amount of fertiliser nutrients and DOM contained within fluvial waters increased significantly, leading to considerable lowering of bottom water pH within rivers and streams. Within the Coal River, the current distribution of pH was obtained, with areas of intermediate pH becoming confined to the intertidal zone, and with low pH occurring in the subtidal zone. As in the 1960's the lowering of pH levels was greatest within the affected rivers and streams; however, a greater connectivity of low pH waters between these rivers/streams with low pH waters in the main body of the upper estuary, as well as the greater contribution of nutrients and DOM from fluvial waters, lead to a slight lowering of pH within the rest of the upper estuary. This may have contributed to the demise of the oyster bed in the mouth of Duckhole Rivulet at this time, although increased

water turbidity and sedimentation (as will be explained later) were mainly responsible. The nutrient content of sandy muds within Midway Bay increased significantly, and was probably accompanied by an appropriate lowering of pH in the area.

During the 1980's, pH levels decreased significantly within the main body of the upper estuary. This occurred with the expansion of low pH into shallower subtidal waters, and by intermediate pH moving into shallow subtidal and intertidal waters. High pH water became absent except in very shallow subtidal-intertidal areas adjacent to seagrass (which had also decreased significantly in distribution). This overall change in pH is a result of the increased delivery of fertiliser nutrients and DOM by fluvial waters to the relatively stagnant waters of the upper estuary. As had previously occurred within rivers and streams, algal and bacterial growth enhanced by fertiliser nutrients, and the decomposition of such organisms, lead to increased oxygen consumption within the waters of the upper estuary. Stagnation enhanced the accumulation of oxygen-depleted waters, such that pH levels decreased over a greater area. This lead to the thinning out or disappearance of clam shell beds within the upper estuary. Within the sandy muds of Midway Bay, nutrient content increased greatly, indicating that the very low pH of the area decreased further, and that the area of very low pH within the upper estuary probably increased slightly.

By the 1990's, the distribution of bottom water pH had reached its modern distribution within the upper estuary. Areas of very low and low pH expanded, and intermediate pH became confined to the intertidal zone. This is, once again, mainly attributable to the increased supply of fertiliser nutrients and DOM by fluvial waters, but it may also be related to increased water stagnation within the upper estuary since construction of the Craigbourne Dam in 1985. Additionally, an overall reduction in rainfall in the catchment area over the last thirty years probably increased water stagnation within the upper estuary, assisted the lowering of pH.

Clam shell beds, already having thinned out or disappeared in the 1980's, became absent from the subtidal waters of the upper estuary, with clams remaining, in low density, only within the intertidal zone.

Before the 1940's, as indicated below the shell layer within the Samphire Island core, a period occurred in which pH was intermediate, preventing clam shell growth and accumulation. It is not known when this period began, and it is not recorded in the other cores. However, peaks in foraminiferal abundance within the Midway Bay core during the 1920's and 1930's, indicative of minor peaks in fertiliser nutrients delivered to the upper estuary, may possibly coincide. An increase in fertiliser nutrients and DOM content within fluvial waters being delivered by the Coal River during that time may have been

accompanied by a lowering of pH within such waters, possibly causing calcite dissolution such that clam growth and accumulation could not occur.

Figure 13.3 displays suggested pH conditions within the lower estuary in 1968 and 2002. The 1968 map was produced from Harris (1968) using the ratio of agglutinated to calcareous foraminifera, and indicates that pH was generally high, with only minor areas of intermediate to high pH occurring within Iron Creek Bay, and in one area to the west of Woody Island. This indicates that in 1968, within rivers/streams emptying into the lower estuary, pH was only slightly lowered by fluvial waters.

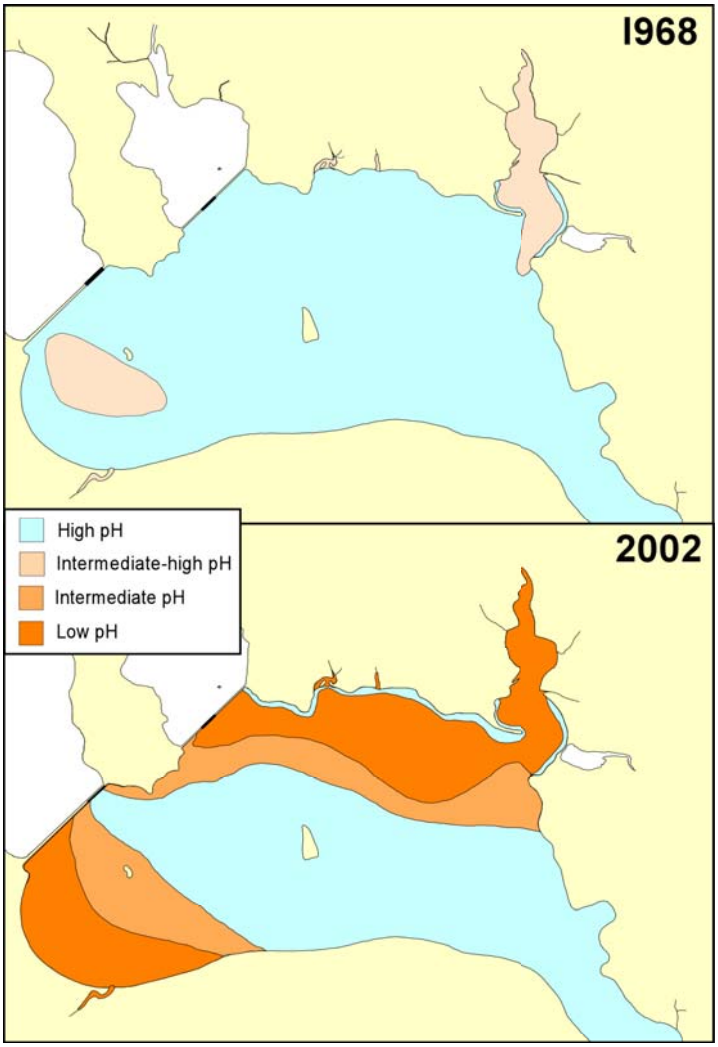

Figure 13.3. Suggested pH distribution within the lower estuary in 1968 & 2002.

Since 1968, pH has decreased considerably within most rivers and streams, in Iron Creek Bay, as well as within quieter, shallower areas of the lower estuary, away from the estuary mouth. It is likely that an increase in fertiliser nutrients and DOM supplied by fluvial waters (particularly from Iron Creek) since 1968 has lead to the development of these areas

of low pH, within which calcite dissolution of calcareous foraminifera occurs. The low pH within Iron Creek Bay is a direct result of its proximity to fluvial waters; however, within the main body of the lower estuary, areas of low pH correlate with areas outside of the main flood tidal current pattern. These areas are relatively stagnant, yet not originally stagnant enough for anoxia to occur. However, with the increased supply of nutrients to these areas, primary production increased, leading to a depletion of oxygen. The low energy conditions of these areas allowed pooling of anoxic water, leading to a lowering of pH levels, thereby having a significant effect upon the benthic fauna.

Observations made by Prestedge (1995) indicate that an increase in algal growth occurred within the lower estuary after the early 1980's, coinciding with the decline in seagrass distribution. Such an increase in algal growth can be seen as evidence of the increase in primary production which lead to the lowering of pH. Additionally, as seagrasses produce oxygen, the loss of significant amounts of seagrass within the lower estuary may have contributed to the increase in water anoxia.

Reduced river flow into the lower estuary caused by diversion of flow for irrigation and/or the decrease in rainfall in the catchment area over the last thirty years could have increased water stagnation within the lower estuary since 1968. Such would have assisted in the pooling of anoxic waters within the lower estuary, thereby, promoting lowered pH conditions.

13.1.2.2. Mud distribution and abundance

The distribution and abundance of mud within the estuary has changed significantly over the last hundred years, with a general increase in the mud content of sediments. The first change, recorded in the Midway Bay core, occurred within the upper estuary following construction of the Midway Bay causeway in 1874. A significant increase in the accumulation of mud, compared to sand, occurred in the surficial sediments of Midway Bay from 1882 to 1907, where mud content increased by 15%. Increased water stagnation within the upper estuary, caused by the causeway, allowed increased settling of suspended sediment. As the age of the base of the Midway Bay core (1882) is younger than that when the causeway was constructed, the actual increase in mud content probably exceeded the amount recorded. Relatively consistent mud content throughout the rest of the core indicates that the sediments of the upper estuary have not become any muddier, and that the effects of the causeway in restricting tidal exchange, thereby maintaining lower energy conditions than would otherwise occur, have continued to the present day.

During the late 1960's to early 1970's, a significant increase occurred in the mud content of sediments within rivers and streams entering the estuary, indicative of an increase in topsoil exposure within the catchment area, following an increase in agricultural activity, and also as a result of the 1967 bushfires. Within the Coal River, adjacent to Samphire Island, a 70% increase in mud content occurred. It is unknown how much mud content increased in other rivers and streams which enter the estuary, but it is likely to have been significant, though less than in the Coal River as it has the largest catchment area of all the rivers and streams. Also at this time, mud content increased, though to a much lesser extent, within river/streams mouths, as well as at subtidal depths within the upper estuary. The increase in mud content at shallow subtidal depths within the mouth of the Duckhole Rivulet was only 5%, and the increase in other areas of the upper estuary was also likely to have been slight. The Midway Bay core indicates that within the sandy muds of the upper estuary, there was no increase in mud content at this time.

During the mid-1970's to 1980's, the mud content of sediments within the Coal River decreased gradually, and was appearing to be reaching stability before increasing again during the late 1980's to early 1990's. This period coincides with the construction of the Craigbourne Dam in 1985 and the establishment of the South-east Irrigation Scheme in the late 1980's. The former increased water stagnation within the estuary; whereas, the latter increased agricultural activity, thereby producing more topsoil exposure and sediment runoff. The increase in mud content within the Coal River was significant, though substantially less than during the late 1960's to early 1970's. Within the mouth of Duckhole Rivulet, the increase was even less. Since the early 1990's, the mud content of sediments within the Coal River and mouth of the Duckhole Rivulet, has decreased, and appears currently to be stable.

The above mentioned trends in mud distribution relate mainly to the upper estuary, as it was from there that short cores were obtained. Trends within the lower estuary have been found by comparison with the study of Harris (1968). Since 1968, mud has a greater, more downstream distribution within the basinal area between the causeways and Woody Island, and patches of intertidal-shallow subtidal, muddy areas have disappeared. The former trend is indicative of increased water stagnation within the estuary. Over the last thirty years, rainfall within the catchment area has decreased substantially which, with the construction of the Craigbourne Dam and establishment of the South-east Irrigation Scheme in the late 1980's, has lead to a general reduction in river flow. Lower energy conditions within the lower estuary have probably allowed the settling of more suspended sediment, leading to

increased mud distribution. Additionally, an increase in mud delivered to the estuary since the late 1960's, may also have contributed to the increase in mud distribution.

The disappearance of intertidal-shallow subtidal areas of mud within the lower estuary, and its replacement with clean sand, is a result of the loss of seagrass since the late 1970's to 1980's. Increased nutrient loading of fluvial waters lead to increased algal growth within the lower estuary. It is likely that this has contributed to the demise of seagrass throughout the entire estuary (together with increased fine sediment settling) as algal growth upon leaves and stems reduces photosynthesis. The distribution of seagrass within the lower estuary in 1968 correlated with the intertidal-shallow subtidal areas of mud, indicating that the loss of seagrass since then has removed the protection from current action which seagrass afforded fine sediment settling.

13.1.2.3. Nutrient content of sediments

Within the modern estuarine environment, the amount of nutrients contained in sediments is reflected by the amount of mud it contains, and is expressed by the abundance of foraminifera. The foraminifera either feed directly on the nutrients attached to the sediment, or they feed on the increased population of bacteria, algae, diatoms, or other organisms which have fed upon it. Consequently, as the amount of mud generally reflects the amount of water stagnation, and therefore the pH of the bottom water, areas of higher particulate nutrients correlate with areas of lowest pH. However, short core data indicate that the amount of nutrients contained in the muddy sediments of the upper estuary has varied, having generally increased.

Within the Midway Bay core, increasing foraminiferal abundance upcore reflects increasing amounts of nutrients contained in the sediments of stable mud content, and is indicative of the amount of nutrients being transported by fluvial waters into the deeper waters of the upper estuary. Figure 13.4 shows four different zones of foraminiferal abundance, which are suggested to correlate with two periods of increased nutrient supply (mid-1920's to late 1940's; post mid-1970's) and two periods of low nutrient supply (early 1880's to mid-1920's; late 1940's to early 1970's).

These changes in the nutrient supply of the sediment changed foraminiferal species composition, causing a switch from association Ab to C, as the species of the latter association are better able to utilise the high nutrient supply than species of the other association. It is likely that water pH also decreased as nutrient supply increased, with

increased primary production, and the decomposition of organic matter, consuming dissolved oxygen.

The increase in mud content of sediments within the more upstream areas of the upper estuary, is likely to have also further lowered pH levels, by the increase in nutrient content of the muddier sediments. This impact is likely to have been greatest within the rivers and streams, especially during the initial increase in mud content during the late 1960's to early 1970's. This is demonstrated in the Samphire Island core, where association Ab was temporarily replaced during that period by association M as the species of the latter association (like association C) can better utilise the high nutrient content of the muddier sediments than species of association Ab.

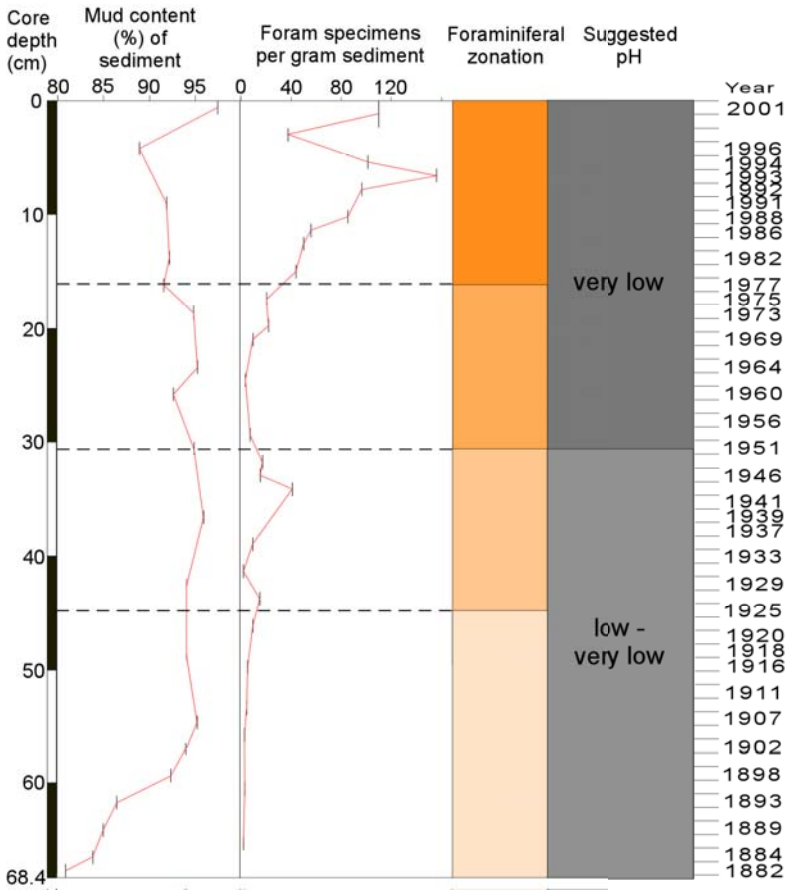

Figure 13.4. Trends and zonation of foraminiferal abundance, reflecting nutrient supply, with resulting changes in bottom water pH, within the Midway Bay core.

13.1.2.4. Average salinity

By comparison with the study of Harris (1968), differences were identified in the upstream and downstream distribution of certain species of foraminifera within the estuary

in 1968 and in 2002. These differences occur in both the upper and lower estuary. Within the upper estuary, the downstream extent of some calcareous species within the Coal River has decreased; whereas, within the lower estuary, there is a greater landward distribution of some marine species. This suggests that there has been a reduction in the downstream extent of flood or high flow waters, with the dilution effects of such fluvial waters now more reduced in downstream extent than in 1968. This has allowed greater upstream penetration by more consistently marine waters within the lower estuary. This has also lead to an increase in species diversity within the lower estuary.

The reduction in rainfall within the catchment area over the last thirty years, in addition to the construction of the Craigbourne Dam (reducing flow and flooding) in 1985 and the South-east Irrigation Scheme (reducing flow volume) in the late 1980's, best explain the reduction in downstream extent of flood or high flow waters in the estuary since 1968.

13.1.2.5. Sedimentation and water turbidity

The method used for dating the short cores assumed a constant sedimentation rate, such that a timeline for each core could be established. It is, however, likely that sedimentation rates varied to some extent at different locations of the estuary at different times. For this reason, the timelines used in each core were used as a general guide, with broader time periods, rather than individual years, used to describe changes.

Prior to the late 1960's, mud content was relatively constant within the sediments of the short cores, and shell (clam and oyster) layers were present. It is likely that this was a period of low sedimentation which enabled shell beds to accumulate within the shallow subtidal waters of the upper estuary. Low turbidity during this period also allowed oyster beds to grow. During this time, sedimentation was, as it is now, greater within the river channels and streams than within the main body of the estuary. This resulted in the shell layers of such environments being less dense than in other localities as they were more dispersed by sediment, and prevented the development of oyster beds.

During the late 1960's to early 1970's, the increase in mud within sediments of the upper estuary was probably accompanied by an increase in sedimentation and water turbidity. An increase in mud content, relative to sand content, either indicates that current strength has decreased substantially, or that the volume of fine sediment being delivered by fluvial waters has increased. The latter explanation is most likely, as indications are that agricultural activity had increased within the catchment during the 1970's, providing more topsoil exposure for erosion by rainwater. Consequently, sedimentation would have

increased at the same time as the increase in accumulation of mud within rivers and streams.

Increased volumes of fine sediment contained within fluvial waters would have also increased water turbidity. There was an increase in the amount of terrestrial plant material contained within sediments of the Coal River at the time, indicating that considerable amounts of organic material were transported by fluvial waters, increasing the amount of material suspended in the water. Additionally, although the increase in mud accumulation within sediments was greatest within rivers and streams, it did also increase in other areas of the upper estuary. Consequently, sedimentation and water turbidity in such areas is likely also to have increased at that time. The demise of the oyster bed at the mouth of the Duckhole Rivulet is seen as evidence of the increase in sedimentation and turbidity at the location during the mid-1970's.

Since the late 1960's, mud content has remained higher within riverine and shallow subtidal sediments of the upper estuary than it was previously. Therefore, it is likely that water turbidity has also remained higher. The increase in mud content of sediments in such areas during the 1990's would also have been accompanied by an increase in sedimentation and water turbidity. Increased stagnation following construction of the Craigbourne Dam in 1985, in addition to an overall decrease in rainfall within the catchment over the last thirty years, is likely also to have enhanced water turbidity within the upper estuary, with limited flushing of turbid waters. Additionally, the Midway Point causeway, by limiting tidal exchange, has also increased water turbidity by limiting the escape of such waters into the lower estuary and Frederick Henry Bay.

13.2. Anthropogenic activities and natural processes which have changed the seafloor environments of the estuary

The anthropogenic activities and natural processes which have changed the seafloor environments of the Pitt Water Estuary over the last hundred years, are the same as those which were determined in chapter 9 to be currently influencing them. Figure 13.5 summarises the major changes which these activities and processes have created. Possibly the most important of these has been the high sediment and nutrient loads which runoff from agricultural lands has been supplying to the estuary since at least the 1960's. The construction of dams (eg. Craigbourne Dam, Richmond weir) and the decrease in rainfall in the catchment area over the last thirty years, has lowered river flow, increasing water stagnation, which has promoted anoxia, low pH, high turbidity and mud deposition. The

construction of the Midway Bay causeway in 1874 caused an increase in water stagnation within the upper estuary, resulting in increased mud accumulation in Midway Bay, and its continued presence has maintained these stagnant conditions.

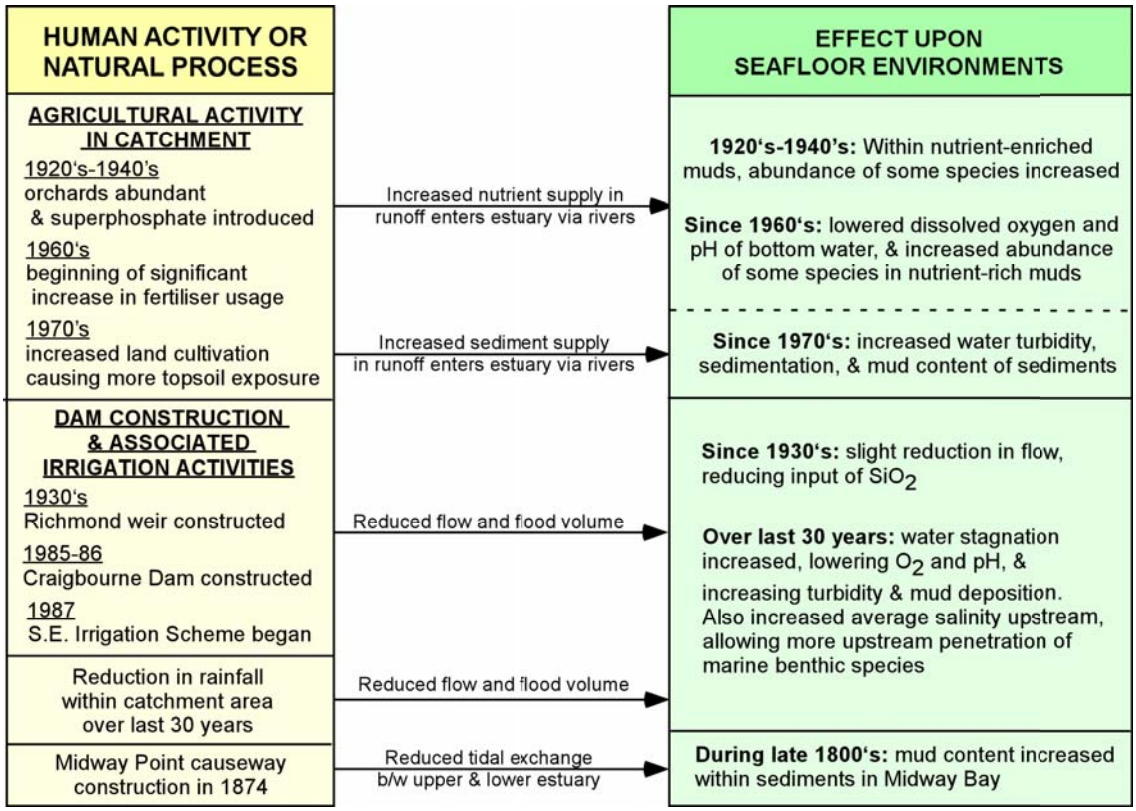

Figure 13.5. Major changes caused by human activities and natural processes to the seafloor environments of the estuary since the 1880's.

13.2.1. Periods of increased agricultural activity

Figure 13.6 shows how, during the 20th century, periods of increased agricultural activity have had an impact upon the sediments and benthic fauna of the estuary. This has occurred via similar processes of change within the estuarine environment as were suggested in Figure 9.9 as currently occurring within the estuary. The main results of increased agricultural activity are increased sediment and nutrient loads supplied to the estuary via runoff from catchment lands. The sediment load is derived from soil loss, following topsoil exposure; whereas, the nutrient load originates from fertilisers used upon such soils, and possibly also from terrestrial plant material.

The short cores have recorded two periods of increased agricultural activity after 1880: from the 1920's to 1940's, and from the 1960's until present day. From the early 1880's to the mid-1920's, the amount of nutrients and sediment being supplied to the estuary was

very low. Between the 1920's and late 1940's, there was a significant increase in the amount of nutrients being supplied to the sandy muds of the upper estuary. This period correlates with the maximum number of orchards operating within the catchment, and with the introduction of superphosphate to agricultural lands. There was no increase in the supply of mud to the deeper areas of the upper estuary, yet more nutrients (derived from fertiliser) were attaching to the suspended sediments within the upper estuary, causing an increase in foraminiferal abundance within areas of mud deposition. There is no record of whether sedimentation increased within the rivers at this time, although a section of the Samphire Island core suggests that pH within rivers may have decreased to some extent due to the increase in nutrient supply. Within the deeper areas of the upper estuary, bottom water pH was already low to very low due to the anoxic, stagnant water conditions, yet it decreased even further due to the increase in primary production spurred by the increase in nutrients within the muddy sediments.

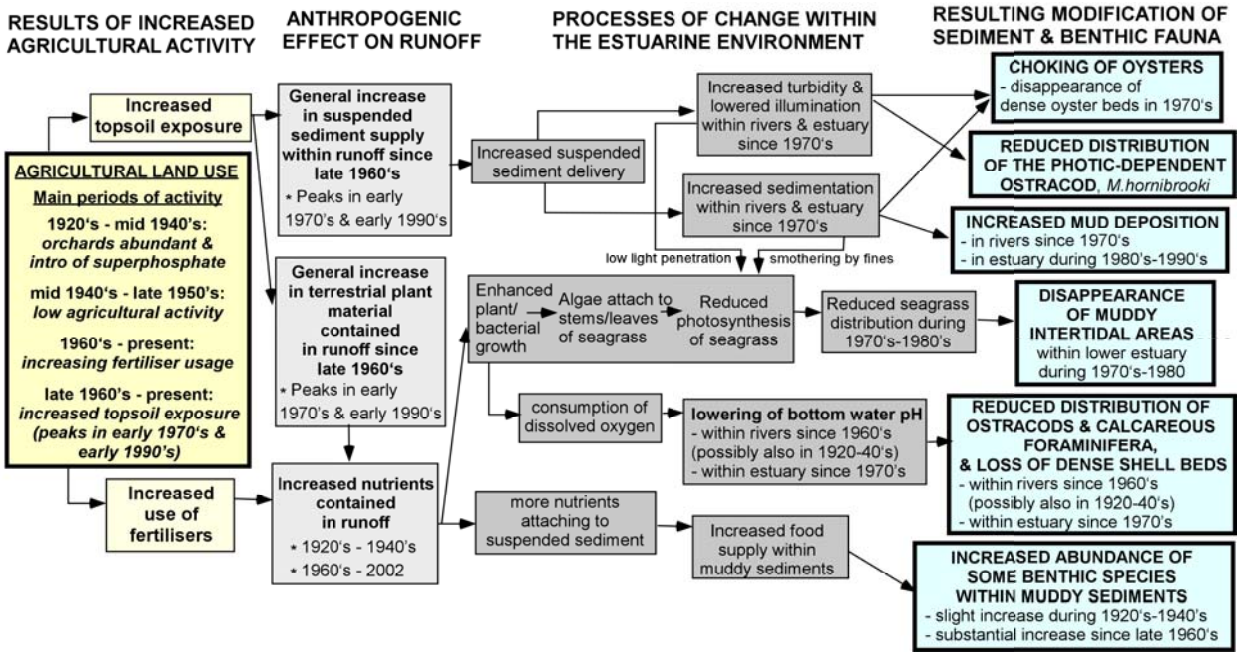

Figure 13.6. The effects of agricultural activity upon the estuary during the 20th century.

During the 1960's, there was a significant increase in the amount of nutrients being delivered to the estuary, suggesting that fertiliser usage within the catchment area increased. This caused an immediate decrease in bottom water pH within rivers and streams, reducing the distribution of ostracods and calcareous foraminifera, and eliminating dense shell beds from such areas. Within the muddy sediments of the upper

estuary, there was an increase in foraminiferal abundance, due to the increased amounts of nutrients attaching to fine sediment.

During the late 1960's to early 1970's there was a increase in suspended sediment loads within fluvial waters, indicative of increased topsoil exposure within the catchment area due to increased land cultivation (but possibly also related to the clearing of vegetation by bushfires in 1967). This caused an increase in sedimentation within rivers and streams, and a slight increase within more upstream shallow subtidal areas of the upper estuary which, with a general increase in water turbidity, caused the elimination of dense oyster layers within the upper estuary. Fertiliser nutrients increased within fluvial waters during the 1970's, leading to a further lowering of pH within rivers and streams. The accompanying increase in primary production also lead to dense algal growth upon seagrass stems and leaves within the estuary, reducing photosynthesis, and subsequently reducing seagrass distribution within the estuary. Additionally, the greater amount of nutrients attaching to fine suspended sediment in fluvial waters, lead to a high abundance of foraminifera within muddy areas of the estuary.

During the 1980's, fertiliser usage within the catchment area continued to increase, leading to a reduction in bottom water pH throughout the upper estuary, causing the thinning of shell beds, and a further reduction in the distribution of calcareous foraminifera and ostracods. During this time, the distribution of seagrass became significantly reduced due to the combination of turbidity, sedimentation and increased algal growth (resulting from high nutrient supply in the estuarine waters) upon stems and leaves, reducing photosynthesis. This lead to the loss of intertidal mud from the lower estuary, due to the disappearance of intertidal seagrass, which had protected such areas from current flow, allowing the settling of fine sediments. The abundance of foraminifera within sandy muds of the upper estuary increased even further.

The establishment of the South-East Irrigation Scheme in the late 1980's, lead to an immediate increase in cropping within the catchment area, leading to a further increase in nutrient supply, and an increase in sediment delivery to the estuary. This further decreased bottom water pH within the estuary, with calcareous foraminifera and ostracods becoming restricted to very shallow subtidal depths within the upper estuary, and reduced distribution within the lower estuary. Dense shell beds disappeared, and the mud content of sediments increased within rivers and streams, and shallow subtidal areas of the upper estuary.

13.2.2. Dam construction and associated irrigation activities, and reduced rainfall

Figure 13.7 shows how dam construction and irrigation activities, together with a reduction in rainfall within the catchment area over the last thirty years, have reduced river flow and the size, frequency and duration of floods within the estuary. The increase in water stagnation and reduced ability of floodwaters to flush the estuary of nutrient-enriched, low pH waters, and suspended sediment, has contributed to the same modifications of sediment and benthic fauna within the estuary as those created by agricultural activities (Figure 13.7). The impact of damming upon river flow has been greatest since the construction of the Craigbourne Dam in 1985, and the reduction in rainfall has occurred over the last thirty years. Consequently, the last thirty years has been a period in which the impact of reduced river and flood flow has been greatest upon the sediments and benthic fauna of the estuary.

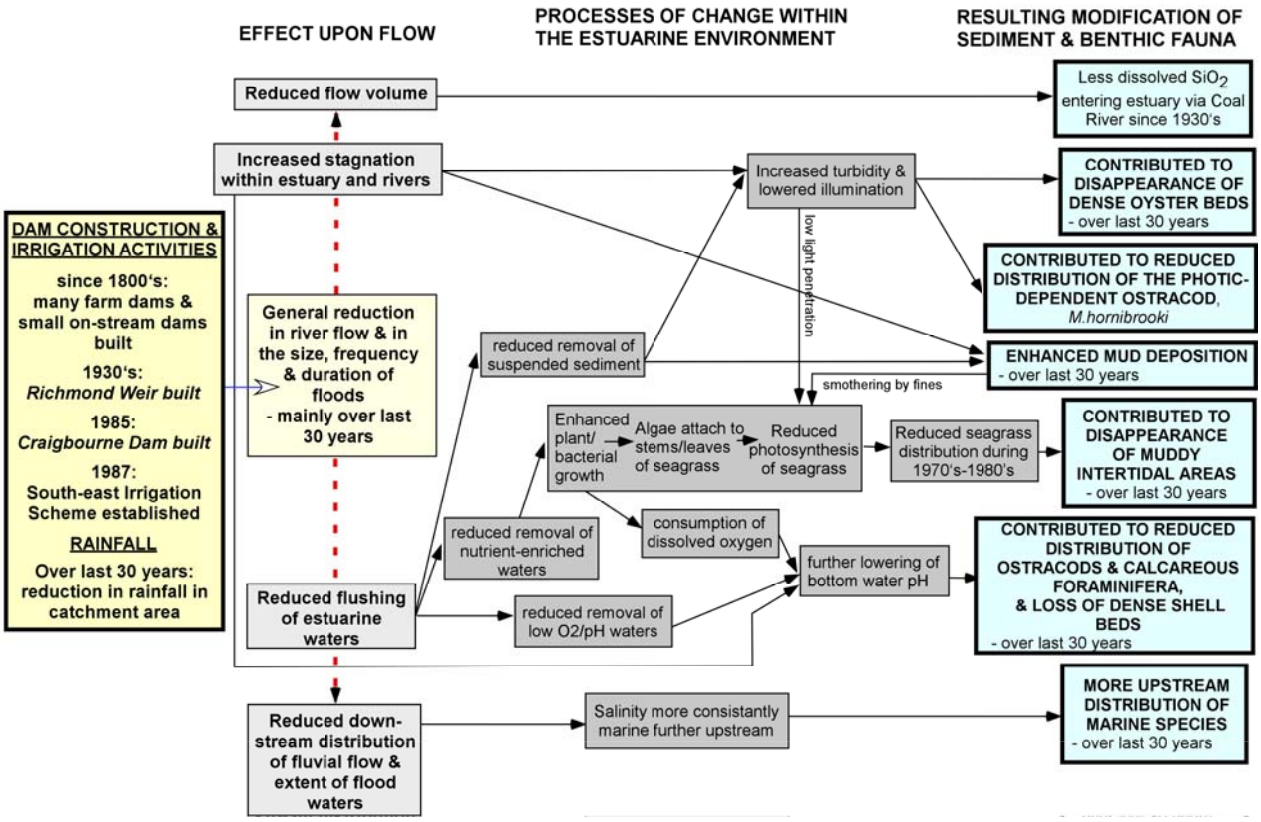

Figure 13.7. The effects of dam construction, irrigation activity, and reduced rainfall upon the estuary during the 20th century.

In addition to increasing water stagnation and floodwater flushing, a general reduction in flow also reduced the downstream distribution of fluvial flow and the extent of

floodwaters. This has resulted in more consistently marine conditions further upstream than previously, leading in turn to a greater upstream distribution of marine species. This change in benthic fauna distribution was determined from comparing analysis of the current study with those of Harris (1968), indicating that it occurred sometime between 1968 and 2002.

The construction of a weir near Richmond in the 1930's caused a reduction in flow on the Coal River. Lane (2004) determined that this was responsible for reducing the amount of dissolved silicate entering the estuary since that time, as evidenced by declining diatom abundance within the Midway Bay core. No other effects of this weir upon the estuarine environment could be determined from the sediments, foraminifera and ostracods of the short cores.

As discussed in 9.2.3, the decline in rainfall within the catchment area over the last 30 years cannot be confirmed with certainty as having been a consequence of global warming, or a result of natural regional climate variability. Therefore, the decrease in river flow resulting from decreasing rainfall cannot be confirmed as being either of natural or anthropogenic origin.

13.2.3. Causeway construction

Figure 13.8 displays the effect the Midway Bay causeway has had upon the estuary since it was constructed in 1874. The causeway has had a major affect upon estuarine hydrology, by reducing tidal exchange, and therefore, water stagnation within the upper estuary, and by impeding the downstream distribution of river floodwaters. The immediate consequence of the causeway construction was a significant increase in the mud content of sediments within Midway Bay. Between 1884 and 1898, mud content increased from 81 to 93%, as a direct result of the increase in water stagnation within the upper estuary.

As only the Midway Bay core records the immediate years following the construction of the causeway, there is no record of how it immediately affected shallow subtidal sediments and benthic fauna in the upper estuary. However, since 1874, it is likely to have contributed to the same modifications of sediment and benthic fauna displayed in Figure 13.7, as it has maintained stagnant water conditions within the upper estuary and has continued to restrict the flushing efficiency of the estuary. The general reduction in river flow over the last thirty years is likely to have made these effects of the causeway more pronounced.

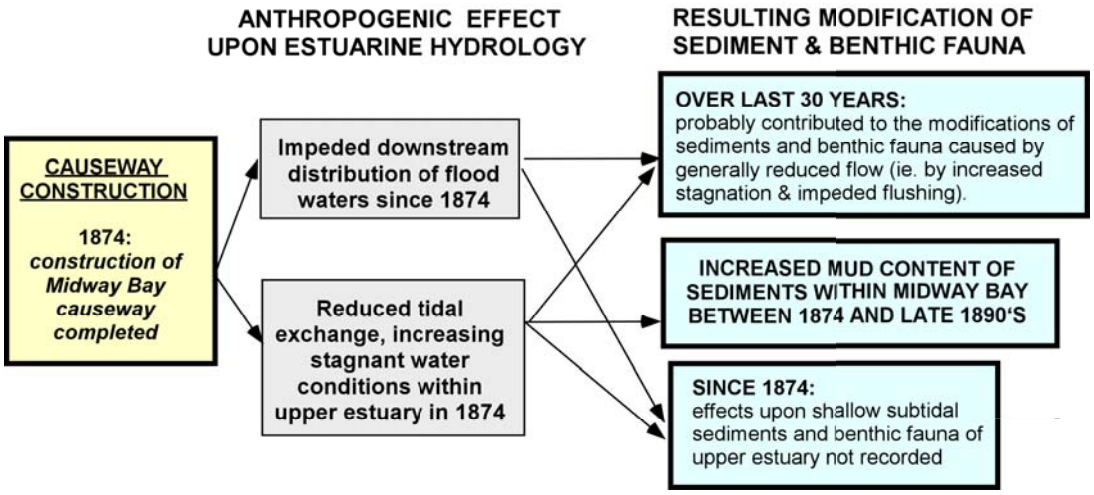

Figure 13.8. Effect of the Midway Bay causeway construction upon the estuary since 1874.

13.3. Summary and Conclusions

Since the 1880's a number of major changes have occurred to the seafloor environments of the Pitt Water Estuary. The most important of these include: an overall increase in the mud and nutrient content of sediments, increased sedimentation and water turbidity, decreased bottom water pH and dissolved oxygen, and increased average salinity in more upstream areas. The benthic fauna have changed in response to these changes in environmental factors, with dense native oyster beds disappearing as a result of increasing turbidity and sedimentation. Dense clam shell beds have disappeared, and the distribution of ostracods and calcareous foraminifera has reduced, mainly because of declining pH levels. The abundance of some foraminiferal species increased dramatically in muddy sediments which became enriched in nutrients.

Mud content of sediments increased significantly within Midway Bay between the early 1880's and late 1890's, due to an increase in water stagnation within the upper estuary. During the 1920's to 1940's, an increase in nutrients supplied by fluvial waters lead to increased nutrient content of muddy sediments within the deeper areas of the upper estuary, with a subsequent increase in foraminiferal abundance in such sediments.

During the 1940's, pH was high within the lower estuary, and varied from very low to high in the upper estuary due to water stagnation, with low pH conditions being restricted to deeper, more stagnant, anoxic waters. Bottom water pH was generally higher than today, and sedimentation and turbidity were low, such that dense shell beds were present at many shallow subtidal depths within rivers and the estuary itself. These shell beds contained a high abundance of ostracods and calcareous foraminifera.

During the 1960's, a lowering in pH occurred within the rivers of the upper estuary, as fluvial waters delivered increased nutrient loads. Within the Coal River, dense clam shell beds disappeared, and a severe reduction occurred in ostracod and calcareous foraminifera, with agglutinated foraminifera becoming more abundant. During this time, within the estuary, a slight lowering of pH levels occurred, and foraminiferal abundance increased steeply within muddier sediments due to an increase in the nutrient contents of sediments.

During the 1970's, a further, considerable lowering in bottom water pH occurred within the rivers of the upper estuary, with a further increase in nutrient loads delivered by fluvial waters. Within the Coal River, the current distribution of pH became established, and a further, slight lowering of pH occurred within the rest of the upper estuary. Foraminiferal abundance increased even further within muddier sediments due to the increase in the nutrient content of sediments. During the early 1970's, a substantial increase occurred in the mud content of sediments within rivers and streams entering the estuary, accompanied by an increase in sedimentation and turbidity. Mud content, turbidity and sedimentation also increased, though much less so, within river/stream mouths, as well as at subtidal depths within the upper estuary, but did not increase within the sandy muds of the upper estuary. By the mid-1970's the mud content of sediments within the Coal River began to decrease gradually; however, the increase in sedimentation and turbidity lead to the demise of oyster beds in the upper estuary. A greater, more downstream distribution of mud within the basinal area between the causeways and Woody Island since 1968, appears related to both increased stagnation in the area, and the increase in mud delivered to the estuary.

During the 1980's, pH levels decreased significantly within the main body of the upper estuary, and in areas of stagnant water away from the mouth within the lower estuary. Greatly increased delivery of nutrients by fluvial waters lead to enhanced algal and bacterial growth within the upper and lower estuary leading to increased oxygen consumption within areas of stagnant water, leading further to a decrease in pH levels over a greater area. This lead to the thinning out or disappearance of clam shell beds within the upper estuary, increased restriction of ostracods and calcareous foraminifera, wider distribution of agglutinated foraminifera, and increased abundance of the latter within muddier sediments. At the end of the 1980's, the mud content of sediments within the Coal River and the mouth of Duckhole Rivulet increased again, though less than in the 1970's. The disappearance of seagrass from shallow, muddy areas within the lower estuary since the late 1970's, lead to a replacement by clean sand as a result of the loss of protection from current action seagrass afforded fine sediment settling.

By the 1990's, the distribution of bottom water pH had reached its modern distribution within the upper and lower estuary. Clam shell beds, already having thinned out or disappeared in the 1980's, vanished from the subtidal waters of the upper estuary, with clams remaining, in low density, only within the intertidal zone. Since the early 1990's, the mud content of sediments within the Coal River and mouth of the Duckhole Rivulet, has decreased, and appears to be currently stable.

Sometime over the last 30 years, the downstream extent of flood or high flow waters has become reduced due to a general decrease in river flow, leading to greater upstream penetration of more consistently marine waters. This has resulted in an increase in the upstream distribution of marine benthic species.

The anthropogenic activities and natural processes which currently influence the seafloor environments of the estuary, are the same as those which have changed them over the last hundred years: agricultural activity, dam construction and irrigation activities, rainfall, and causeway construction.

The increase in sediment and nutrient loads supplied by fluvial waters is a direct result of agricultural activity. Increased topsoil exposure resulting from increased land clearing and cultivation since the late 1960's, and possibly burning of significant areas of vegetation by bushfires in 1967, lead to increased soil loss in the catchment, and increased sediment loading in fluvial waters. This has lead to increased mud content of sediments, and increased water turbidity and sedimentation. Increased usage of fertilisers within agricultural areas initially in the 1920's to 1940's (when orchards were abundant and superphosphate was introduced) and overall since the 1960's, has lead to unnaturally high nutrient loads within fluvial waters, causing increased primary production within rivers/streams and the estuary, in turn leading to a general decline in bottom water pH, and high nutrients in muddy sediments. The establishment of the South-east Irrigation Scheme in 1990, caused an immediate increase in cropping within the catchment, and a consequent further increase in nutrient supply, and in increase in sediment delivery to the estuary.

The construction of dams (such as Craigbourne Dam in 1985) and a decrease in rainfall within the catchment area over the last thirty years, have generally reduced river flow and the size, frequency and duration of floods. This has contributed to increasing anoxic water conditions, thereby, further reducing bottom water pH. It has also enhanced mud deposition, particularly within the lower estuary, and restricted the ability of river floods to flush the estuary of low pH, nutrient-enriched, turbid waters. It has also lead to more consistently marine conditions occurring further upstream than previously, leading to a

greater upstream distribution of marine species. The last thirty years has been a period in which the impact of reduced river and flood flow has been greatest.

The construction of the Midway Bay causeway in 1874 had a major effect upon estuarine hydrology, by reducing tidal exchange, thereby increasing water stagnation within the upper estuary, leading to an increase in mud content in sediments within Midway Bay during the late 19^{th} century. Its continued presence has maintained these stagnant conditions and impedes the downstream distribution of river floodwaters.

CHAPTER 14. FUTURE DEVELOPMENT OF THE ESTUARY

14.1. Introduction

In this chapter, the probable response of the Pitt Water Estuary to possible scenarios during the 21st century is examined. These scenarios will arise from global warming and altered land use, with the former causing increasing sea level, temperature, and evaporation, altered rainfall and wind regime.

14.2. Global warming

The Intergovernmental Panel on Climate Change (IPCC, 1996) concluded that the increasing concentration of greenhouse gases within the atmosphere since pre-industrial times has lead to, and will continue to increase, global warming. Furthermore, in the Third Assessment Report (TAR) of the IPCC (2001) it was concluded that global warming has occurred over the last century, and there is new and stronger evidence that most of the warming over the last 50 years is attributable to human activities (Pittock, 2003). Consistent with this observed warming over the last century, has been a rise in global average sea level and ocean heat content (Pittock, 2003). Higher temperatures are also likely to be accompanied by increased evaporation, and altered rainfall patterns.

Development has reduced the area and water quality of many estuaries, increasing the vulnerability of their ecosystems to sea level rise and climate changes (Pittock, 2003).

14.2.1. Sea level

During the 20th century, there was a global average sea level rise of 1-2 mm per year, equivalent to a total rise of 10 – 20 cm (IPCC, 2001). Historic 1840's tide gauge records from Port Arthur, Tasmania, suggest that from 1841 to 2002, average sea level rise in the south-east of the state has been about 0.8 mm per year (Hunter et al., 2003). However, the rate of rise appears to be increasing, with the CSIRO (2001) reporting an average sea level rise around Australia for 1920-2000 as 1.2 mm per year. Additionally, during 1950-2000, the global sea level rise was about 1.8 mm per year (IPCC, 2001).

Projections by IPCC (2001) are for a global average sea level rise of between 9 and 88 cm by 2100 relative to 1990. Additionally, sea level is expected to rise beyond 2100, as deep

oceans continue to warm due to generally warmer global average temperatures (Pittock, 2003).

Within the Pitt Water Estuary, increasing sea level during the 21st century will cause the inundation of low-lying coastal areas, with the expansion of the subtidal zone, and shoreward shifting of the intertidal zone. This will have a significant effect upon the distribution of sedimentary environments within the estuary, as it changes the distribution of current strength and relative current energy. In the central basin, increasing water depth and/or increasing distance from the shoreline, would make wind-generated wave action weaker (than it is currently) within the deeper areas of the upper estuary, such that the mud content of sediments would increase in such locations. Additionally, increasing water depth within the lower estuary would maintain greater tidal current strength, such that total current energy would probably increase, perhaps increasing mean sand grain size upon the marine tidal delta. Furthermore, the size of the marine-dominated zone would increase, expanding further upstream and further shoreward. The central basin and river-dominated zones may grow shoreward as sea level rises, but would probably only shift (rather than expand) further upstream. This could mean that quartzose sand distribution would expand further upstream within the estuary; whereas, lithic sand distribution would shift further upstream.

Figure 14.1 displays a coastal vulnerability map constructed by Sharples (2004) for the Pitt Water Estuary. It indicates which areas of the estuary are potentially susceptible to sandy shore erosion and recession, and increased storm surge flooding. The geomorphological impacts of increasing sea level will generally have less effect upon rocky shorelines than upon beaches or other unconsolidated coastal deposits, and increasing sea level is likely to cause increased storm surge flooding (Sharples, 2004). According to Figure 14.1, Seven Mile Beach, Five Mile Beach and various other sandy shore areas of the estuary are likely to erode and recede as sea level increases; whereas, many areas of the upper estuary, and the spit, are likely to be subject to increased storm surge flooding.

Bird (1993) has noted that estuaries and lagoons will initially tend to widen and deepen as sea level rises, however, there will also be a concurrent tendency for flood-tidal deltas to grow upwards so as to keep pace with sea level rise (Sharples, 2004). This means that the marine tidal delta of the Pitt Water Estuary should grow and translate landwards as sea level rises; however, Sharples (2004) suggests that marram grass binding of dune sand on the spit may create a sand budget deficit, which will reduce the sand supply necessary for such an expansion, causing accelerated erosion of the already eroding sandy shores of

Dodges Ferry and Five Mile Beach. Therefore, with increased erosion and recession also occurring at Seven Mile Beach, there is likely to be an overall narrowing of the spit of the estuary as sea level rises.

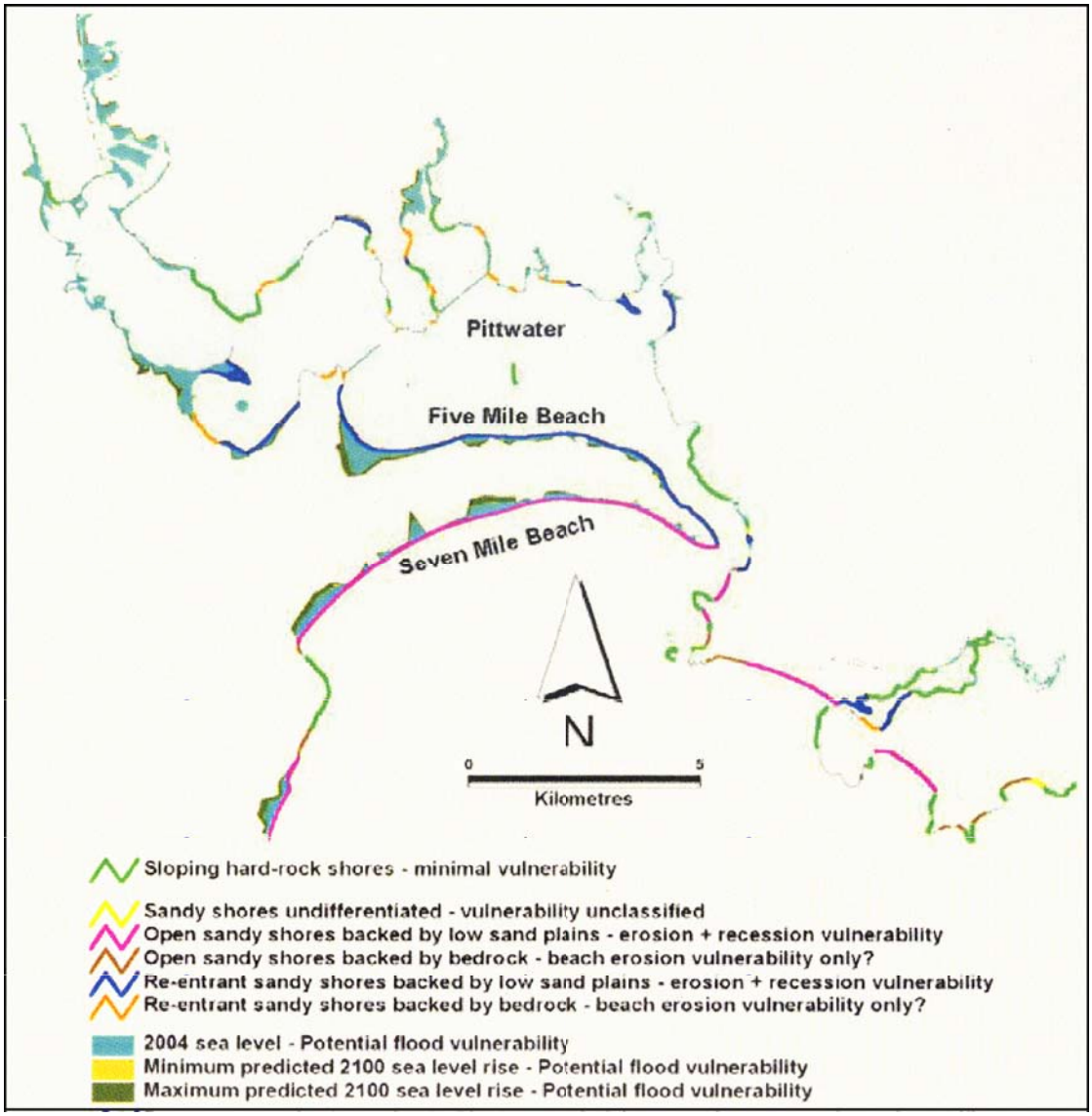

Figure 14.1. Indicative coastal vulnerability map for the Pitt Water Estuary, showing coastal areas potentially susceptible to storm surge flooding and sandy shore erosion and recession (from Sharples, 2004).

In muddy, low-lying shores of the estuary, the shoreline will regress unless the supply of sediment keeps up with the rising sea level. This may mean that within the river-dominated areas of the estuary, the shoreline may not change significantly if sediment supply is sufficient, although in areas of the central basin, the shoreline is more likely to prograde. Currently, sedimentation rates within the mouth of Duckhole Rivulet are 0.575 cm per

year; whereas, in Midway Bay it is 0.542 cm per year, and in the Coal River adjacent to Samphire Island it is 1.355 cm per year. An increase in global sea level by 2100 of between 9 and 88 cm (relative to 1990) equates to between 0.08 and 0.8 cm sea level rise per year. It is likely that sedimentation within the Coal River (and other rivers) will keep ahead of sea level rise, such that (assuming current levels of sediment supply) in river deltas, shoreline progradation will not occur but rather regression will continue (though at a lower rate than currently). In less river-dominated, subtidal areas of the upper estuary, sedimentation is close to the median of the range of sea level rise over the 21st century. This suggests that, given current levels of sediment supply, sedimentation may possibly keep up with sea level rise, such that water depth may not increase substantially. In sandy sediments of the marine delta, sedimentation is low, and the growth of the delta under sea level rise will cause erosion of nearby sandy areas such as Five Mile Beach.

The effects of sea level rise upon the benthic fauna of the estuary would mainly be a result of increasing water depth (if it were to occur), and the shifting of the intertidal zone. Intertidal and shallow subtidal faunas would gradually move shoreward; whereas, deeper subtidal faunas would expand in areal distribution. Increasing tidal current energy within the lower reaches of the estuary, resulting from rising sea level, may lead to more consistently marine conditions occurring further upstream, thereby promoting greater upstream distribution of marine species. Additionally, if water depth were to increase within the upper estuary, it might increase the distribution of more stagnant water, such that lower bottom water pH may have a greater distribution, excluding ostracods and calcareous foraminifera from a larger area.

14.2.2. Temperature

Australian average temperatures have risen by 0.7 °C over the last century (Pittock, 2003). Global temperatures are likely to rise by between 1.4 and 5.8 °C by 2100 (CSIRO, 2001). In Australia, annual average temperatures could be 0.4 to 2.0 °C higher in 2030 compared to 1990, and by 2070 annual average temperatures could be 1.0 to 6.0 °C higher (CSIRO, 2001). Warming is likely to be greatest in spring and least in winter (CSIRO, 2001).

Within the Pitt Water Estuary, water temperature varies considerably according to seasonal changes in air temperature. Consequently, the majority of benthic species within the estuary are tolerant of a wide range of temperatures, and may not necessarily be directly affected by the general increase in water temperature during the 21st century.

14.2.3. Rainfall, evaporation, and water balance

Projections of annual rainfall for Australia by CSIRO (2001), predict little change for Tasmania, however, seasonal changes are likely to occur. In Tasmania, winter rainfall may increase, with a projected range of –5 to +20% by 2030, and of –10 to +60% by 2070 (CSIRO, 2001). In contrast, spring, summer and autumn rainfall rainfall is likely to decrease (-10% to +5% by 2030; -35% to +10% by 2070) (Pittock, 2003).

Higher temperatures are likely to increase evaporation, especially in warmer months. Projections of change in potential evaporation by CSIRO (2001) showed increases in all seasons, annually averaged up to 12% per degree of global warming within Tasmania. The difference in potential evaporation and rainfall gives a net atmospheric water balance (Pittock, 2003). CSIRO (2001) projected decreases in water balance on a national basis, with decreases of 15 to 160 mm by 2030, and 40 to 500 mm by 2070. Nunez (2004) highlighted the likelihood of increased evaporation in the north and east of Tasmania during the warmer months, increased evaporation in most of the state during summer, and a decline in water balance in the eastern half of the state.

It is possible that such a decline in water balance within eastern Tasmania may result in a decrease in runoff within the catchment of the Pitt Water Estuary during the 21st century. This decrease in runoff would be greatest in warmer months, as it is during then that the decline in rainfall, and the increase in evaporation, is greatest. Decreasing runoff would lead to a reduction in river flow which would increase water stagnation within the estuary and its rivers, and reduce the downstream distribution of fluvial flow. Such would enhance mud deposition, reduce the distribution of calcareous foraminifera and ostracods, and increase the upstream distribution of marine species (see Figure 9.10, and 13.6 for process of changes).

CSIRO (2001) models simulate an increase in extreme daily rainfall leading to more frequent heavy rainfall events in Australia, which are likely to be associated with increased flooding. This would suggest the possibility of increasing flood frequency within the estuary. Such would increase the flushing of estuarine waters, removing suspended sediment, and nutrient-enriched, low pH waters, thereby, reducing mud accumulation, and enhancing the distribution of calcareous foraminifera and ostracods.

14.2.4. Carbonate concentration in ocean

Increasing atmospheric carbon dioxide concentrations will lead to a decrease in the carbonate concentrations of the ocean, reducing the calcification rates of corals (Pittock,

2003). It is possible that it may also have an effect upon the growth rates and survivability of calcareous foraminifera and ostracods within the Pitt Water Estuary, possibly by reducing their distribution, particularly where pH levels are already low enough to cause some calcite dissolution.

14.2.5. Wind

A greater frequency of high wind events (such as storms) is likely to occur in Australia during the 21st century (Pittock, 2003). Storm surges are likely to be more common because of higher mean sea level and increased storm intensities (Pittock, 2003). Consequently, it could be expected that the shoreline of the estuary may suffer greater wave attack. Such would have greatest effect upon the shoreline of Seven Mile Beach where wave action is always greatest, and where increasing sea level would already be causing erosion and receding of the sand barrier.

Elsewhere within the estuary, a greater frequency of high wind events would lead to more frequent resuspension of muddy sediments at shallow depths, possibly reducing mud accumulation. It would also promote more longshore drift of sandy sediments, and lead to increased erosion on sandy beaches.

14.3. Changing land use (agricultural, urban)

It is difficult to predict how land use may change within the catchment area over the 21st century. Agricultural activity has already reached a peak, with the establishment of the South-east Irrigation Scheme in the late 1980's. Much of the forest within the catchment has been cleared already, and mud content in many areas of the estuary appears to have stabilised in recent years, with the last peak occurring immediately after the South-east Irrigation Scheme was established.

The sediment and nutrient loads being delivered by rivers to the estuary will vary in the future mainly according to changes in agricultural activity, with an increase in agricultural activity increasing loads, and a reduction in activity reducing loads. However, improved fertiliser usage techniques and products in the future, could help lessen an increase in nutrient loads.

In 14.2.1 it was suggested that, at current sediment supply rates, sedimentation within the river deltas of the estuary will exceed sea level rise, and that in less river-dominated, muddy areas of the upper estuary, sedimentation will probably keep up with sea level rise.

This is based upon the assumption that sedimentation within these parts of the estuary remains at current levels. Therefore, if agricultural activity were to decrease within the catchment at some stage during the 21st century, shoreline progradation within the river deltas is more likely to occur, and water depth would increase further in the deeper areas of the upper estuary.

It is likely that increasing urbanisation will have a significant effect upon the estuary during the 21st century. Townships within the catchment area have grown considerably over the last twenty years, and continue to grow. Possibly the greatest effect this will have upon the estuary will be an increase in the amount of pollutants contained in stormwater entering the estuary. Such pollutants can include: suspended solids (dust, soil and sediment etc), fuel, oil, lubricants, exhaust emissions, and heavy metals contained in road runoff, detergents and oils from washing and maintaining vehicles, nutrients from inappropriate fertiliser usage, pet wastage, and general rubbish, such as plastics and packaging materials. Unless steps are taken to prevent such pollutants from entering the estuary, a significant impact is likely upon the benthic fauna of the estuary. The likely effects of this are a decrease in species diversity and abundance, altered species composition, and more morphological deformation of tests. An increase in mud content of sediments would also be expected, as well as an increase in heavy metals.

14.4. Summary and Conclusions

During the 21st century, the biggest threats to the estuary are likely to be global warming and changing land use. The effects of global warming upon the estuary will mainly be caused by rising sea level and altered water balance in the catchment area. Inundation of low-lying areas will occur, with erosion and recession of sandy beaches (causing narrowing of the spit), and landward growth and translation of the marine tidal delta. Within the upper estuary, sedimentation (if continuing at current rates) is likely to keep pace with the rising sea level; whereas, within the sandy areas of the lower estuary (where sedimentation is low) water depth is likely to increase. Greater tidal current energy is likely to occur in the lower estuary, expanding the marine-dominated zone, such that quartzose sands and marine benthic species will have a more upstream distribution.

A decline in water balance projected for eastern Tasmania, may lead to a decrease in river flow into the estuary. This will lead to increasing water stagnation, declining bottom water pH (reducing distribution of ostracods and calcareous foraminifera), and increasing

upstream penetration of marine species. However, increased flooding will occur as a result of more frequent heavy rainfall events in Australia.

It is likely that sediments and nutrients will continue to be supplied by rivers to the estuary from the catchment area, although the amount supplied will vary according to changes in agricultural activity. Rapidly increasing urbanisation is likely to become a problem, with more pollution being supplied to the estuary via stormwaters.

CHAPTER 15. SUMMARY AND CONCLUSIONS

This study describes the modern and Recent distribution of seafloor environments within the Pitt Water Estuary using the distribution of sedimentary facies and foraminiferal and ostracode assemblages, examined from both modern surficial and short core sediments. This multidisciplinary research identifies the environmental factors currently influencing the seafloor of the estuary, and describes the current anthropogenic influence upon them. It also describes how the seafloor of the estuary has changed over the last 100 years, and relates these changes to historic human activities or natural processes. Therefore, as well as providing an understanding of the dynamics of the modern estuarine environment, this study shows how humans have changed, and continue to change, the estuary.

15.1. Modern seafloor environments

Aim #1:

Describe the modern seafloor environments of the estuary using the distribution of sediments, foraminifera and ostracods

A suite of 86 sediment samples, obtained from the seafloor of the estuary, allowed identification of modern sedimentary facies, and foraminiferal and ostracod assemblages (sample & species associations), which characterise modern seafloor environments by inferring sedimentary environments and benthic habitat zones.

(a) The distribution of sedimentary environments

A dual classification scheme was used to generate sedimentary facies, firstly using Entropy analysis to group particle-size distribution data into groups distinguished by contrasting mud content and/or sand grain size, and secondly by classifying sediments by sand composition (lithic, quartzose, or mixed). Ten sedimentary facies were identified, and define sedimentary sub-environments, which were combined to identify four major sedimentary environments: the riverine channel, fluvial delta, central basin, and marine tidal delta.

The river channels contain muddy sands with a high lithic sand content. Sand transport probably occurs during floods or periods of higher river flow, with mud falling out of suspension and accumulating in layers during intervening periods.

The fluvial deltas contain muddy sands or clean sands, with high lithic sand content, and are considerably reworked. Sands are derived from fluvial flow at times of higher river

flow or flooding, or are derived from shoreline erosion as a result of wind-generated wave action.

The central basin is the largest major depositional environment, containing three main zones: (a) an estuarine basin located between the Midway Point causeway and the fluvial deltas; (b) a marine-dominated subtidal zone, located between the causeway and marine tidal delta; and (c) a zone of mixed estuarine - marine conditions adjacent to the causeway. The estuarine basin has sands of intermediate-high lithic sand content, and contains three further sub-environments: deep, subtidal sandy muds; shallower subtidal and tidal flat muddy sands; and intertidal clean sands. Within the estuarine basin, marine and fluvial influences are minor, and water circulation and sediment movement are determined by wind-generated waves. The marine-dominated subtidal basin is a wave and tide-influenced subtidal zone of the central basin, and lower energy extension of the marine tidal delta. It contains sand transported upstream by tidal currents, and mud deposited during still phases in the tide cycle. The mixed fluvial-marine subtidal zone surrounds the causeway channel, with sediments containing a mixture of mud, lithic sand brought downstream through the channel, and quartzose sands brought upstream by tidal currents.

The marine tidal delta zone is located within the estuary mouth, containing clean, quartzose sand derived from Frederick Henry Bay and the Seven Mile Beach Spit, consisting of four sub-environments: the inlet channel, lower- and higher-energy tidal flats and mixed lithic-quartzose beach sands. The inlet channel is a narrow and deep, high energy environment, containing shelly, medium-grained sands. Lower energy tidal flats represent the majority of the marine tidal delta zone, consisting of shallow subtidal and intertidal fine sand flats. Mixed lithic-quartzose beach sands occupy the intertidal zone along the northern and eastern shoreline of the lower estuary, consisting of fine - medium grained sand, essentially of marine origin, yet also containing lithics derived from shoreline erosion. Higher-energy tidal flats occur on the northern and western sides of the inlet channel upon shoaling beds, containing coarser sand than that of the lower-energy tidal flats due to the presence of greater tidal currents, combined with wave action.

(b) Distribution of foraminifera (general trends, sample & species associations)

(i) General foraminiferal trends

Species diversity of foraminifera is higher within the deeper and/or more seaward areas of the lower estuary where marine influence occurs; whereas, it is lowest in the intertidal zone, high energy channels, and the deeper, muddier, turbid areas of the upper estuary and Orielton Lagoon. The abundance of foraminifera is lowest at shallow subtidal and

intertidal depths where conditions are variable and subject to wave/tidal agitation; whereas, it is greatest in the inlet channel (due to low sedimentation rate) and in muddier sediments (due to high nutrient content providing an abundant food source). Planktonic foraminifera are restricted to the mouth and deeper subtidal areas landward of the mouth within the lower estuary, where there is marine influence over hydrology and sedimentation. Agglutinated foraminifera dominate much of the upper estuary, and shallow subtidal areas away from the mouth within the lower estuary, where water stagnation and/or nutrient-enrichment of bottom water and sediments, creates anoxic conditions, in which pH is lowered, such that calcareous tests are preferentially dissolved. Calcareous foraminifera dominate the intertidal zone (where stirring by wind oxygenates the water), and the deeper and/or more seaward areas of the lower estuary, where marine waters are well oxygenated.

(ii) Foraminiferal sample associations

Twelve foraminiferal sample associations (Eh, Ap, AbAp, Ab, C, AbEe, Aa, M, Ec, AaEw, AbEc, R) were identified by Q-mode cluster analysis, and are assemblages which represent the grouping of samples from similar ecological environments.

Sample association Eh is confined to shallow subtidal and intertidal depths within the estuary mouth (being the most marine association), and has the greatest abundance and diversity of calcareous species, containing a mixture of marine and estuarine species typical of a marginal marine environment. Sample association Ap represents a marine influenced upstream extension of the mouth of the estuary, is dominated by calcareous foraminifera, and contains a mixture of marine and estuarine species indicative of marginal marine conditions which are less marine-influenced than within the mouth. Sample association AbAp represents a transitional environment between deeper, marginal marine (Ap) and shallower, lagoonal (Ab) associations, having intermediate species composition, and mixed agglutinated-calcareous foraminiferal content, indicative of intermediate bottom water pH due to some stagnation and nutrient-enrichment of the water.

Sample association Ab occurs in low-energy shallow subtidal areas of the upper and lower estuary which are subject to little or no marine influence; the fauna has low diversity and high agglutinated foraminiferal content, indicative of low bottom water pH due to stagnation and nutrient-enrichment of bottom water and muddy sediments. Sample association C is restricted to the deepest, muddiest, most stagnant and turbid areas of the upper estuary; the fauna has very low species diversity and very high agglutinated foraminiferal content, indicative of very low bottom water pH, and little or no marine influence. The abundance of foraminifera is high due to the nutrient-enriched muds

promoting productivity. Sample association AbEe occurs in low-energy, shallow subtidal, sloped areas of the upper estuary, transitional between associations Ab and C, in which the mixed agglutinated-calcareous foraminiferal fauna is indicative of low bottom water pH which is sometimes raised by turbulence following flood events. Sample association Aa is located within a narrow, relict channel within the upper estuary known to be affected during flooding events, and contains a 'dead assemblage' derived by post-mortem transport from neighbouring associations. Sample association M occupies the mouths of rivers or streams, and contains a fauna indicative of low-energy, nutrient-enriched, anoxic, low pH waters, and high freshwater influence. Association M also occurs at the western end of Five Mile Beach due to sheltered conditions, and proximity to a local stream.

Sample association Ec is mainly confined to the northern shore of the lower estuary, and Orielton Lagoon, in which the variable, stressful conditions are reflected by a low diversity fauna, in which calcareous foraminifera dominate due to the constant stirring processes by tidal movement and wind-generated wave action, keeping bottom water oxygenated, and thereby keeping pH levels high. Sample association AaEw occurs in intertidal waters at the eastern end of the northern shore of the lower estuary, and contains a calcareous foraminiferal fauna indicative of more marine influence than the adjacent intertidal association Ec. Sample association AbEc dominates the intertidal zone of the upper estuary, in conditions more stressful than those of the lower estuary and Orielton Lagoon, due to intertidal waters being more sheltered, less well-stirred, and therefore, less well oxygenated and with lower pH, such that a mixed calcareous-agglutinated foraminiferal fauna occurs.

Sample association R is present in the high energy, Inlet and Midway Point causeway channels, with the dominant species able to attach to the hard substrate.

(iii) Species associations

Seven species associations (A – G) and one ungrouped association were identified by R-mode cluster analysis, and are assemblages formed by the grouping of species of similar environmental preferences, reflecting a common set of ecological conditions.

Species association A is the most widespread species association, occurring in low-energy, poorly oxygenated areas of the estuary away from the mouth. Association B occurs in the deepest, muddiest sediments and lowest-energy conditions of the estuary; whereas, association C is most abundant within the deeper waters of the lower estuary between the mouth and Woody Island. Association D has limited distribution, being present only in the middle section of the estuary at intermediate subtidal depths; whereas, association E

mainly occupies the estuary mouth and the intertidal zone further upstream. Association F occupies most intertidal areas, as well as some shallow subtidal areas within the upper estuary, and within the marine-influenced zone of the lower estuary. Association G occupies the inlet and causeway channels; whereas, the ungrouped association occurs in one sample obtained from Barilla Rivulet, being typical of low salinity, riverine conditions.

(c) Distribution of Ostracoda (general trends, sample & species associations)

(i) General ostracod trends

The areal distribution of species diversity and abundance of ostracods is very similar to that of foraminifera; however, values are generally less, indicating that ostracods are less capable of withstanding the stressful conditions of the estuary. Ostracods are absent from the inlet channel (due to high current speeds) and within the muddiest sediments of the upper estuary and Orielton Lagoon (due to the bottom water pH causing total calcite dissolution).

(ii) Ostracod sample associations

Nine ostracod sample associations (MhPz, XcMt, MhMp, MhMtMp, MtMh, Mp, LhPs, Mh, MhAv) were identified by Q-mode cluster analysis.

Sample association MhPz is the outermost association, occurring just within Frederick Henry Bay, and contains the most diverse, and abundant, ostracod assemblage, consisting of a mixture of marine and estuarine species typical of a marginal marine environment. Sample association XcMt is located at Okines Beach within the estuary mouth, sharing a similar fauna to MhPz, yet one indicative of shallower, more sheltered and lower energy, marginal marine conditions. Sample association MhMp mainly occupies the deeper subtidal areas of the lower estuary, representing a marine influenced, upstream extension of the mouth, and contains a mixture of marine and estuarine species indicative of marginal marine conditions which are less marine-influenced than within the mouth. Sample association MhMtMp is mainly confined to the lower estuary, representing a transitional environment between deeper, marginal marine (MhMp) and shallower, lagoonal (MtMh) associations, and containing a fauna intermediate in composition between the adjacent associations.

Sample association MtMh occupies low-energy shallow subtidal areas within the lower estuary, upstream of the mouth, in which there is less marine influence, and contains a fauna of low diversity and abundance, indicative of stressful conditions in which there is

evidence that low bottom water pH causes dissolution of ostracod valves. Sample association Mp occupies most subtidal areas in the upper estuary (apart from the deepest areas where no ostracods occur), and contains a fauna of low diversity and abundance, which reflects low bottom water pH conditions, and little or no marine influence. Sample association LhPs occupies the mouths and lower reaches of rivers and streams, and contains a low diversity fauna which is indicative of significant freshwater influence, and low pH levels due to generally low river flow, and nutrient-enrichment of the water.

Sample association Mh represents the intertidal zone in all areas of the estuary except Iron Creek Bay, containing a fauna of low diversity and abundance, which reflects the highly variable conditions of intertidal depths. Sample association MhAv was obtained from intertidal waters in the mouth of Iron Creek Bay, and the fauna is indicative of more marine influence than in the other intertidal association.

(iii) Species associations

Six species associations (A – F) were identified by R-mode cluster analysis.

Species association A is restricted to the Midway Point Causeway and Sharks Point channels, being absent from the inlet channel. Association B occupies the most seaward area of the lower estuary, being most abundant at subtidal depths within the estuary mouth, yet absent from the intertidal zone and the inlet channel. Association C is the most widespread, occupying all intertidal areas, in addition to subtidal depths within the lower estuary; whereas, association D occupies much of the subtidal zone of the upper estuary, yet also occupies deeper subtidal depths within the lower estuary away from the mouth. Association E occurs at subtidal depths between the estuary mouth and Sharks Point, being most abundant adjacent to the inlet channel within the mouth, and in deeper subtidal areas between the inlet channel and Midway Point causeway. Association F is restricted to subtidal and intertidal depths within, or proximal to, river mouths and channels.

Aim #2:

Describe the current distribution and influence of environmental factors which control the distribution of the modern seafloor environments.

The seafloor environments of the Pitt Water Estuary vary according to two major physical parameters (upstream distance, and water depth) which correspond to a suite of environmental factors which directly influence the surficial sediments and benthic fauna. These factors may vary with either, or both, physical parameters, affecting the sediments and/or the benthic fauna.

Surficial sediments are mainly influenced by relative current energy and current strength. Relative current energy varies mainly with upstream distance and determines the composition/origin of the sand; whereas, current strength can vary with both upstream distance and water depth and determines the texture of the sediment (i.e. the sand grain size and mud content).

Average salinity and current strength (mainly relating to pH) are the most important factors influencing the benthic fauna. Variation from normal marine salinity only occurs within the main body of the estuary during flood events, by which salinity is considerably lowered, decreasing further upstream. Increasing tolerance to lowered salinity is a characteristic of benthic fauna found with upstream distance within the estuary.

Current strength mainly affects benthic fauna by generating anoxic conditions in stagnant waters, causing lowered bottom water pH, which causes dissolution of calcareous tests. The effects of this are greatest within deeper areas of the upper estuary and Orielton Lagoon, in which Ostracoda and calcareous foraminifera are absent. Current strength can also affect benthic fauna by creating substrate mobility within high energy channels and the intertidal zone, favouring species with anchorage ability, or robustness, respectively.

Illumination is an important influence upon the depth distribution of Ostracoda, limiting some species to the photic zone, which is narrow within the upper estuary due to high turbidity. Nutrient supply is greater in muddier sediments and increases the abundance of inhabiting species, as well as further decreasing bottom water pH. In contrast, seagrass can raise pH levels, by oxygenating otherwise anoxic waters, and is also favoured by some normally rare species. Tolerance to tidal exposure and varying water temperature also influence the distribution of some species.

Aim #3:

How have human activities affected the controlling environmental factors, thereby, altering the natural distribution of sediments, foraminifera and Ostracoda in the estuary?

Current anthropogenic modifications to the estuary and its catchment have altered the modern estuarine environment by disrupting the natural river flow regime and flow volume, altering the natural estuarine water circulation pattern, and increasing greatly the supply of mud and nutrients delivered to the estuary. These human activities include agricultural and urban land use within the catchment area, dam construction on rivers and the associated irrigation of adjacent lands, and the presence of the Midway Bay and Sorell

causeways. A reduction in rainfall within the catchment area over the last thirty years (of either natural or anthropogenic origin) has also contributed to a reduction in flow volume.

The main effect such activities have had upon the natural surficial sediment distribution, is greatly increased mud deposition and accumulation, especially within the upper estuary and Orielton Lagoon. Additionally, sandy substrates have been formed within the narrow openings of each of the causeways.

Alterations of the natural estuarine environment resulting from human activities, which have affected the distribution of benthic species (mainly within the upper estuary and Orielton Lagoon) include: high turbidity, low dissolved oxygen, low pH, high mud deposition, and the increased nutrient content of sediments. Alteration of these environmental factors has lead to a reduction in the natural distribution of photic-dependent benthic species, ostracods and calcareous foraminifera, and to a lesser extent, those species which prefer a seagrassed substrate. Increased abundance of some species, tolerant of low pH conditions has also occurred as a result of increased nutrient content in muddy sediments.

Alteration of natural river flow regime and flow volume has increased the average salinity (especially in more upstream areas), and has caused conditions within the lower estuary to be more consistently marine. As a consequence, there is currently a greater, than is natural, upstream distribution of marine species, in particular, of euryhaline species which prefer more marine salinity, and of stenohaline species.

15.2. Recent seafloor environments

Aim #1:

What historical changes have occurred to the seafloor environments of the estuary?

Four short cores, collected from the upper estuary, were sub-sampled, with sediments and shell content described, and foraminiferal and ostracod assemblages identified, thereby allowing analysis of the change in seafloor palaeoenvironments at specific sites. Comparison was also made between the current study and a similar study from 1968, allowing description of overall changes in the estuary since then.

Since the late 19th century, major changes have occurred to the seafloor environments of the estuary, including: an overall increase in the mud and nutrient contents of sediments, increased sedimentation and water turbidity, decreased bottom water pH and dissolved oxygen, and increased average salinity in more upstream areas. These changes have

affected the benthic fauna, with increasing turbidity and sedimentation eliminating dense native oyster beds, and with declining bottom water pH levels eliminating dense clam shell beds and reducing the distribution of ostracods and calcareous foraminifera. Nutrient-enrichment of muddy sediments has drastically increased the abundance of some foraminiferal species.

Within Midway Bay, from the early 1880's to late 1890's, sediments became muddier after an increase in water stagnation within the upper estuary; whereas, during the 1920's to 1940's, increased nutrient loading of fluvial waters increased the nutrient contents of the muds, leading to increased foraminiferal abundance. In the 1940's, bottom water pH was generally higher than today, and sedimentation and turbidity were low, such that dense shell beds were present at many shallow subtidal depths within rivers and the estuary itself. Bottom water pH was high within the lower estuary, but varied from very low to high within the upper estuary due to deeper waters being more stagnant and anoxic.

In the 1960's, increased nutrient loading of fluvial waters lead to a significant lowering of bottom water pH within rivers, where dense clam shell beds disappeared, the abundance of ostracods decreased, and the abundance of agglutinated foraminifera increased relative to calcareous foraminifera. Within the upper estuary, a slight lowering of pH levels occurred, and increasing nutrient content of muddy sediments lead to a significant increase in foraminiferal abundance.

In the 1970's, a further lowering of bottom water pH occurred in rivers, as nutrient loads increased more within fluvial waters. Modern pH distribution was established in the Coal River and, in the upper estuary, a further, slight lowering of pH occurred, and foraminiferal abundance increased even more within muddier sediments. An increase occurred in suspended sediment loading of rivers during the early 1970's, which lead to a significant increase in mud content, sedimentation and turbidity within rivers and streams, and a slight increase within river/stream mouths, as well as at subtidal depths within the upper estuary. However, by the mid-1970's, the mud content of sediments within the Coal River began to decrease, although sedimentation and turbidity were still high enough to lead to the demise of oyster beds in the upper estuary. At this time, the distribution of mud also increased within the deeper areas of the lower estuary due to high sediment loading of fluvial waters and increased water stagnation.

In the 1980's, a further increase in nutrient loading of fluvial waters lead to a significant lowering of bottom water pH within the main body of the upper estuary, and in areas of stagnant water away from the mouth within the lower estuary. This caused the disappearance of clam shell beds in the estuary, more reduced distribution of ostracods,

increased distribution of agglutinated foraminifera relative to calcareous foraminifera, and increased abundance of foraminifera in surficial muds. In the late 1980's, sediments again became muddier within the Coal River and in mouth of Duckhole Rivulet, though less than in the 1970's.

The modern distribution of bottom water pH in the estuary was reached in the 1990's. The current mud content of sediments within the Coal River and mouth of the Duckhole Rivulet, is less than in the early 1990s, and appears to be stable.

Sometime over the last 30 years, a general decrease in river flow has lead to greater upstream penetration of more consistently marine waters, such that marine benthic species have developed a more upstream distribution.

Aim #2:

What human activities or natural processes have caused these changes?

The human activities and natural processes which currently influence the estuary have been changing it since the late 19th century, including: agricultural activity, dam construction and irrigation activities, rainfall, and causeway construction.

Agricultural activity has increased the sediment and nutrient loads of fluvial waters. Since the late 1960's, increased land clearing and cultivation (and possibly the 1967 bushfires), have lead to increased topsoil exposure and subsequent soil loss, with more fine sediment entering fluvial waters, leading to an increase in mud content of sediments, and increased water turbidity and sedimentation. Increased fertiliser usage in the 1920's - 1940's (when orchards were abundant and superphosphate was introduced) and especially since the 1960's, has increased nutrient loads in river waters, leading to a general decline in bottom water pH, and high nutrient content in muddy sediments. The South-east Irrigation Scheme, established in 1987, resulted in an immediate increase in cropping, leading to a further increase in nutrient and sediment delivery to the estuary.

The construction of Craigbourne Dam in 1985, and decrease in rainfall within the catchment over the last thirty years, has reduced river flow and the size, frequency and duration of floods, thereby contributing to more anoxic water conditions (further lowering bottom water pH), enhancing mud deposition, and restricting the flushing of low pH, nutrient-enriched, turbid waters. It has also lead to greater upstream penetration by more consistently marine conditions, and therefore, by marine species.

Construction of the Midway Bay causeway in 1874 had an immediate effect upon estuarine hydrology, reducing tidal exchange, and increasing water stagnation within the

upper estuary. This lead to an initial increase in the mud content of sediments in Midway Bay over the next twenty years.

15.3. Future development of the estuary

Aim #1:

What is the possible future of the seafloor environments of the estuary?

During the 21st century, global warming and changing land use are likely to be processes responsible for the majority of long-term changes in the estuary. Global warming will increase sea level, with low-lying areas becoming inundated, sandy beaches eroding and receding, and the marine tidal delta moving landward. If sedimentation remains at current rates within the upper estuary, it is possible water depth will not change considerably; however, it is likely to increase in the lower estuary where sedimentation is low. Increasing tidal current energy in the lower estuary, is likely to expand the marine-dominated zone, such that quartzose sands and marine benthic species will have a more upstream distribution.

Global warming is also likely to lead to a decline in water balance in eastern Tasmania (CSIRO, 2001), which may lead to a decrease in river flow into the estuary. The resulting increase in water stagnation may further reduce bottom water pH, reducing the distribution of ostracods and calcareous foraminifera, and increasing the upstream penetration of marine species.

Increasing urbanisation of the catchment area during the 21st century may possibly lead to a significant increase in pollution being supplied to the estuary via stormwaters. However, changes in agricultural land use are likely to remain the strongest controls on the amount of sediments and nutrients being supplied to the estuary.

15.4. Recommendations for future work

This study provides a benchmark for comparison with other Tasmanian estuaries, as well as with the estuary itself again in future years.

Similar studies of other Tasmanian estuaries (e.g. Derwent Estuary, Oyster Bay, Tamar River, Huon Estuary, Boat Harbour) could accurately describe current estuarine health and dynamics, making them a valuable contribution to any environmental impact assessment. Additional palaeoenvironmental reconstructions will add to the understanding of the long-term impacts of environmental change upon coastal environments. These studies would

increase our understanding of coastal environments in Tasmania, and how we influence them, and provide a “snapshot” of these environments at a given time for future reference. Additionally, more of these studies would expand the environmental knowledge base on Tasmanian Quaternary foraminifera and ostracods, thereby making each successive study more accurate.

By adopting the methodology of the present study, futures studies of the Pitt Water Estuary will be able to describe in detail any environmental changes which have occurred to it since 2002. This has potential to record the effects of global warming upon the estuary over coming decades.

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	Size range (um)																																	
max (um)	2000	1680	1410	1190	1000	840	710	590	500	420	350	300	250	210	177	149	125	105	88	74.0	62.5	53.0	44.0	37.0	31.00	15.60	7.80	3.90	2.00	0.98	0.49	0.24	0.12	0.06
min (um)	1680	1410	1190	1000	840	710	590	500	420	350	300	250	210	177	149	125	105	88	74	62.5	53.0	44.0	37.0	31.0	15.60	7.80	3.90	2.00	0.98	0.49	0.24	0.12	0.06	0.00
Sample	Size range frequency (% weight)																																	
2	0.02	0.04	0.07	0.11	0.24	0.42	0.85	1.80	3.74	6.52	8.01	12.39	14.00	14.37	13.42	11.04	7.46	4.07	1.38	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0.05	1.56	4.30	10.90	17.29	21.07	20.21	14.68	7.35	2.35	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0.01	0.32	2.78	5.69	11.68	15.86	17.93	17.37	14.06	8.88	4.26	1.13	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0.01	0.83	3.34	7.35	9.90	15.68	17.25	16.44	13.54	9.23	4.69	1.62	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	1.13	4.29	10.11	17.33	18.19	21.08	15.30	8.57	3.38	0.62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.24	2.25	7.87	14.94	20.62	21.93	17.65	9.99	3.81	0.69	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0.15	2.33	5.08	11.34	16.61	19.55	18.85	14.38	8.00	3.12	0.58	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0.18	2.45	5.72	13.18	18.97	21.18	18.63	12.41	5.62	1.56	0.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0.02	1.78	4.40	7.88	9.43	13.96	14.96	14.50	12.76	9.86	6.24	3.16	1.02	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0.28	2.53	7.30	14.54	17.07	21.92	17.81	11.37	5.45	1.60	0.13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0.03	1.56	5.66	9.66	17.50	20.37	19.04	14.34	8.20	3.11	0.51	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0.06	0.13	0.14	0.12	0.09	0.11	0.28	1.47	4.10	7.86	9.91	15.13	16.28	15.45	12.87	9.05	4.88	1.89	0.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0.06	1.92	6.15	9.92	17.42	19.97	18.58	14.06	8.15	3.18	0.56	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0.10	1.85	6.10	9.39	13.69	16.98	14.63	15.31	10.96	6.72	3.30	0.92	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0.73	3.90	10.76	15.71	23.48	21.22	14.49	7.21	2.26	0.24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0.07	2.65	6.05	8.18	13.11	14.89	15.00	13.53	10.59	6.75	3.43	1.11	0.06	0	0	0	0.08	1.28	0.62	0.93	0.89	0.63	0.15	0	0	0	0
23	0	0	0	0	0.51	2.69	6.41	9.12	12.80	15.48	13.13	13.59	9.69	5.97	3.00	0.98	0.07	0	0	0	0.08	0.26	0.30	0.28	0.67	1.24	1.56	1.24	0.77	0.16	0	0	0	0
24	0	0	0	0	0	0	0.89	3.78	8.42	14.44	15.68	19.63	16.38	11.40	6.41	2.55	0.42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0.18	2.35	6.64	13.18	15.73	21.01	18.16	12.72	6.98	2.64	0.41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0.47	2.61	5.72	9.49	10.44	13.99	13.38	11.48	8.78	5.73	2.86	0.97	0.07	0	0	0.04	0.37	0.57	2.30	2.54	3.32	2.61	1.50	0.71	0.05	0	0	0
27	0	0	0	0	0	0	0.07	1.89	5.33	10.33	12.40	17.31	16.44	13.37	9.22	5.06	1.92	0.37	0	0	0	0.03	0.36	0.49	1.27	0.77	1.53	1.11	0.61	0.12	0	0	0	0
28	0	0	0	0	0	0.34	3.70	8.20	14.35	19.61	17.39	17.60	11.30	5.61	1.78	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0.01	0.22	1.85	6.39	9.81	17.72	19.60	17.46	12.32	6.86	2.28	0.40	0	0	0	0	0.05	0.34	1.20	0.59	1.10	1.04	0.68	0.08	0	0	0	0
30	0	0	0	0	0	0	0	0.17	1.86	6.37	9.87	17.90	19.62	17.11	11.57	6.08	1.75	0.23	0	0	0	0	0.07	0.39	1.35	0.92	1.80	1.54	0.99	0.41	0	0	0	0
31	0	0	0	0	0	0	0	0	0.53	3.80	9.39	20.73	25.42	21.67	12.84	4.78	0.79	0.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0.03	1.55	5.58	9.46	17.17	20.01	18.88	14.49	8.60	3.48	0.74	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0.08	0.38	0.97	1.75	2.88	4.26	4.69	6.84	7.57	7.86	7.57	6.99	4.34	3	1.46	0.52	0.09	0	0.11	0.46	4.65	6.93	8.42	9.11	6.27	2.52	0.28	0	0	0
34	0	0	0	0	0	0	0	0.15	1.85	4.74	6.94	11.66	13.56	13.65	12.01	8.89	5.11	2.15	0.42	0	0	0	0.18	0.52	2.81	3.2	4.45	3.92	2.4	1.21	0.18	0	0	0
35	0	0	0	0	0	0	0.65	3.05	5.84	8.86	9.33	12.37	12.09	10.95	9.15	6.86	4.32	2.28	0.86	0.2	0.03	0.22	0.42	0.59	2.19	2.02	2.76	2.43	1.56	0.85	0.12	0	0	0
36	0	0	0	0	0	0	0.05	1.74	4.44	8.23	9.76	13.83	13.78	12.12	9.44	6.23	3.21	1.23	0.27	0.01	0.15	0.48	0.7	0.84	2.59	2.26	2.99	2.69	1.83	1.01	0.12	0	0	0
37	0	0	0	0	0	0	0	0.39	3.24	7.14	9.36	14.59	16.05	15.58	13.47	10.03	5.95	2.71	0.63	0.01	0	0	0	0	0	0	0.33	0.34	0.18	0	0	0	0	0
38	0	0	0	0	0	0	0	0.02	1.11	4.33	8	15.56	19.51	19.68	16.12	10.19	4.4	1.05	0.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0.1	3.34	7.64	10.19	15.43	16.02	14.38	11.28	7.5	3.93	1.58	0.39	0.02	0.04	0.28	0.47	0.57	1.55	0.97	1.17	1.22	1.11	0.72	0.1	0	0	0
40	0	0	0	0	0	0	0.03	2.13	4.64	7.63	8.48	11.81	12.06	11.46	10.26	8.51	6.25	4.22	2.47	1.26	0.58	0.29	0.21	0.27	1.42	1.12	1.52	1.54	1.14	0.63	0.07	0	0	0
41	0	0	0	0	0	0	0	0.73	3.22	7.48	10.1	15.61	16.45	14.74	11.2	6.82	2.94	0.7	0.02	0	0	0.04	0.41	0.6	1.82	1.24	1.88	1.73	1.33	0.83	0.11	0	0	0
43	0	0	0	0	0	0	0	0.01	0.31	3.17	8.27	19.32	25.07	22.63	14.29	5.74	1.15	0.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0.95	3.22	7.13	10.55	13.39	15.01	14.68	11.93	8.3	4.55	1.89	0.5	0	0	0.02	1.94	1.52	1.32	1.49	1.01	0.57	0.03	0	0	0
45	0	0	0	0	0	0	0	0	0.28	3.56	7.58	15.85	20.4	20.56	16.53	10.12	4.17	0.93	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0.05	2.33	6.47	12.25	14.38	19.41	17.6	13.46	8.56	4.16	1.24	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0.01	0.98	3.68	6.68	7.86	11.37	12.05	11.81	10.87	9.22	6.9	4.73	2.77	1.4	0.61	0.26	0.13	0.18	1.34	1.55	1.74	1.83	1.3	0.66	0.07	0	0	0
48	0	0	0	0	0	0	0.02	1.78	5.62	11.34	13.91	19.44	18.19	14.28	9.3	4.61	1.41	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0.34	2.88	8.74	14.91	22.9	20.28	12.52	5.09	0.94	0.06	0	0	0	0	0.31	0.63	0.74	1.7	1.18	2	1.9	1.62	1.05	0.21	0	0	0
51	0	0	0	0	0	0	0	0.08	0.13	0.16	0.12	0.56	1.43	2.37	3.35	4.33	4.96	5.37	5.25	4.85	4.31	4.3	3.5	3.13	9.95	9.6	9.63	9.64	7.51	4.56	0.91	0	0	0
52	0	0	0	0	0	0	0	0	0	0.03	0.67	3.23	5.26	7.17	8.71	9.42	8.78	7.35	5.23	3.27	1.87	1.21	0.85	0.98	5.81	6.37	6.91	7.26	5.6	3.36	0.66	0	0	0
53	0	0	0	0	0	0	0	0	0	1.24	3.67	7.06	9	9.94	10	9.15	7.31	5.4	3.51	2.19	1.43	1.31	1.25	1.43	5.6	4.08	5.16	4.9	3.82	2.21	0.34	0	0	0
54	0	0	0	0	0	0	0.02	1.4	4.27	8.26	9.94	14.2	14.17	12.39	9.42	5.89	2.66	0.65	0.01	0	0.26	0.72	0.91	0.99	2.57	2.06	2.87	2.74	2.12	1.24	0.24	0	0	0
55	0	0	0	0	0	0	0.01	0.21	0.44	0.65	0.7	1	1.17	1.33	1.48	1.6	1.57	1.5	1.35	1.19	1.11	1.24	1.22	1.39	8.07	12.08	14.07	16.8	15.85	10.9	3.07	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26	0.81	1.48	2.16	2.91	3.46	3.82	3.99	4.61	4.29	4.26	14.08	11.78	12.03	11.92	10.18	6.57	1.39	0	0	0
57	0	0	0	0	0	0	0.01	0.64	1	1	0.56	0.3	0.04	0.04	0.29	0.87	1.79	2.94	3.96	4.69	5.02	5.71	4.94	4.44	13.56	12.58	10.21	10.27	8.65	5.39	1.1	0	0	0
58	0	0	0	0	0	0	0.65	2.86	6.03	10	11.11	15.06	14.53	12.55	9.71	6.46	3.42	1.38	0.29	0.01	0	0.12	0.31	0.43	1.24	0.64	1.08	0.99	0.77	0.36	0	0	0	0
59	0	0	0	0	0	0	0	0	0.01	0.13	0.6	1.62	2.49	3.21	3.69	3.84	3.53	3.04	2.39	1.84	1.48	1.48	1.33	1.42	8.05	12.61	13.68	14.3	11.21	6.61	1.44	0	0	0
60	0	0	0	0	0	0	0.19	0.97	2.33	3.74	3.87	4.81	4.25	3.47	2.68	2.03	1.53	1.3	1.2	1.18	1.2	1.44	1.42	1.55	7.95	12.62	14.6	11.85	7.93	4.86	1.03	0	0	0
61	0	0	0	0	0	0	0.05	1.37	4.09	8.06	9.79	13.92	13.61	11.47	8.25	4.76	1.89	0.32	0	0	0	0.39	0.64	0.8	2.89	3.44	4.14	4.09	3.37	2.17	0.49	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0.51	0.93	1.43	1.82	2.13	2.39	3.04	3.16	3.54	14.4	13.93	17.2	16.69	11.84	6.06	0.87	0	0	0
63	0	0	0	0	0	0	1.34	4.08	8.5	13.76	14.37	17.44	14.14	9.63	5.29	2.07	0.35	0	0	0	0	0.28	0.42	0.45	1.09	1.41	1.7	1.64	1.31	0.68	0.05	0	0	0
64	0	0	0	0	0	0	0.39	2.64	5.79	9.56	10.47	13.97	13.18	11.03	8.07	4.84	2.04	0.3	0	0.03	0.4	0.87	1.04	1.07	2.64	2.14	3.45	2.88	1.91	1.09	0.2	0	0	0
65	0	0	0	0	0	0	0.7	1.09	1.1	0.73	0.26	0.15	0.41	1.11	2.18	3.45	4.51	5.3	5.42	5.07	4.44	4.23	3.21	2.7	8.63	8.97	9.75	10.2	8.89	5.98	1.52	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0	0.12	1.38	2.91	4.53	5.99	7.31	7.82	7.58	6.83	6.53	4.8	3.7	8.14	7.09	8.15	7.37	5.53	3.52	0.7	0	0	0
67	0	0	0	0	0	0	0	0.06	0.7	0.86	0.59	0.45	0.36	0.79	1.87	3.66	5.79	7.96	9.32	9.65	9.07	8.92	6.51	4.77	7.44	4.87	5.31	4.76	3.58	2.28	0.43	0	0	0
68	0	0	0	0	0	0	0.01	0.98	3.28	5.84	6.85	9.93	10.56	10.28	9.29	7.63	5.45	3.56	2.02	1.09	0.65	0.61	0.6	0.71	3.14	3.42	4.21	4.21	3.3	1.99	0.39	0	0	0
69	0	0	0	0	0	0	0.67	3.31	6.37	9.72	10.15	13.17	12.42	10.8	8.63	6.19	3.76	1.97	0.81	0.3	0.2	0.33	0.43	0.52	1.7	1.6	2.11	2.11	1.66	0.94	0.13	0	0	0
70	0	0	0	0	0	0	0.14	1.04	2.62	4.59	5.39	7.9	8.58	8.73	8.39	7.54	6.07	4.6	3.13	2.04	1.34	1.08	0.83	0.81	3.82	4.82	4.81	5.03	3.99	2.29	0.42	0	0	0

Appendix A. Particle-size distribution data of surficial sediment samples

Sample No.	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	22	23	24	25	26	27	28	29	31	32	33	34	35	36	37	38	39	40	41	42	43
Weight of sample (g)	20.0	21.0	1.4	0.3	30.0	1.7	30.0	0.3	15.0	7.1	1.7	11.5	30.0	30.0	30.0	18.7	30.0	30.0	5.7	30.0	30.0	30.0	12.5	4.1	30.0	39.2	30.0	30.0	20.0	4.9	3.9	3.5	30.0	25.0	25.0	20.0	30.0	3.9	20.0
Total number of specimens	307	582	509	473	327	520	58	388	642	304	286	319	380	324	175	316	83	92	269	85	31	19	201	240	48	553	33	38	645	301	321	373	548	396	274	1052	1316	251	39
Abundance (spec/gm sed)	15.4	27.8	376	1725	10.9	301	1.93	1229	42.8	43.1	165	27.8	12.7	10.8	5.83	16.9	2.77	3.07	44.8	2.65	1.03	0.63	13.8	54.4	1.6	13.4	1.1	1.27	19.7	49.4	71.7	90.4	18.1	15.8	10.1	48	39.5	63.7	1.95
Fisher Alpha Index	7.55	4.28	8.01	2.01	6.95	0.96	5.04	1.64	6.29	4.41	3.09	4.14	2.60	3.67	4.67	3.45	3.87	7.78	4.57	3.34	1.21	1.02	6.64	6.99	2.74	3.08	3.42	1.11	4.42	7.88	8.23	6.64	3.81	1.63	1.09	5.06	7.80	5.80	4.33
% live	2.28	20.1	56.8		59.6		70.7		28	58.2		63.3	20	42.9	13.1	46.2	47	18.5	27.9	43.5	61.3	15.8	8.96	33.8	68.8	30.6	45.5	10.5	8.68	9.97	16.5	34.9	4.93	23.7	1.82	5.42	8.36		25.6
% Planktic	0.66	0.17	0.99	0	0.31	0	0	0	0.63	0.33	0.35	0.63	0	0	1.74	0	0	1.1	0	1.13	0	0	0	0.42	0	0.18	0	0	0	0.34	0.63	0.54	0	0	0	0.1	0.23	0	0
% Agglutinated (of benthic)	0.33	1.38	0	1.69	2.76	0.38	5.17	1.8	1.57	16.8	23.5	14.8	35.8	4.63	9.88	30.1	26.5	12.1	16.4	32.9	93.5	94.7	26	4.2	8.1	9.6	54.5	97.4	60.5	8.87	9.51	21.0	45.0	90.7	98.7	35.9	12.4	11.6	55.9
% Hyaline (of benthic)	98.4	98.5	95.6	93	89	99.6	93.1	97.2	98.3	80.5	74	84.5	62.6	95.4	90.1	69.9	73.5	87.9	78.8	62.4	6.45	5.26	74	93.8	89.1	90.4	45.5	2.63	39.5	91.1	89.1	76	52.2	0.74	0.36	64.1	87.6	87.5	42.7
% Porcellaneous (of benthic)	1.31	0.17	4.37	5.29	8.28	0	1.72	1.03	0.16	2.64	2.46	0.63	1.58	0	0	0	0	0	4.83	4.66	0	0	0	2.01	2.83	0	0	0	0	0	1.42	2.35	2.15	2.61	0.9	0	0	0.92	1.42
Hemisphaerammina bradyi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptohalysis catella	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.2	0	0	0	0.2	0	2.6
Reophax scorpiurus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cuneata arctica	0	0	0	0	0.6	0	0	0	0	0	0	0	0.8	0.6	0.0	0	3.6	0	0	1.2	0	0	0	0	2.1	0	0	0	5.6	1.0	0.9	2.4	1.5	1.8	2.6	1.0	3.6	0	0
Ammobaculties barwonensis	0.3	1.2	0	0	1.2	0	5.2	0	1.2	16.8	2.1	14.7	23.9	1.9	9.1	29.4	13.3	12.0	16.0	29.4	87.1	73.7	22.9	4.2	6.3	9.4	45.5	81.6	40.5	6.0	7.5	15.3	39.6	37.1	84.7	26.9	6.7	9	51.3
Miliamina fusca	0	0	0	0	0.3	0	0	0	0.2	0	0	0	10.8	0.6	0	0.6	7.2	0	0	0	6.5	21.1	0.5	0	0	0	3.0	13.2	7.8	0.3	0	0	1.8	56.8	10.9	4.4	0	0.4	0
Scherochorella barwonensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eggerella australis	0	0	0	0	0	0	0.5	0.0	0.0	3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0.2	0	0	0
Eggerella subconica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0	0
Textularia conica	0	0.2	0	0.6	0	0	0	0	0	2.4	0	0	0.9	0	0	2.4	0	0	0	0	0	0	0.5	0	0	0.2	0	2.6	0.6	0.7	0	0	0.4	0.5	0	0	0	0	0
Textularia earlandi	0	0	0	0	0.6	0	0	0.8	0.2	0	10.5	0	0	0.6	0	0	0	0	0.4	1.2	0	0	1.5	0	0	0	6.1	0	4.7	0.3	0.6	3.5	2.9	2.8	0.7	1.0	1.3	7.2	0
Paratrochammina bartrami	0	0	0	0	0	0.2	0	0	0	0.0	0	0	0	0	0	0	0	0	0.0	1.2	0	0	0	0	0	0	0	0	0.5	0.3	0	0.3	0	0	0	0	0.1	1.2	0
Portetrochammina sorosa	0	0	0	1.1	0	0.2	0	0.5	0	4.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.1	0.8
Trochammina inflata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.1	0	0	0
Buliminoides gracilis	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0
Cibicides refulgens	7.2	12.0	13.4	0	0.6	0	1.7	0	10.7	14.8	0.3	0.6	0	0.6	9.7	0.6	0	4.3	0	0	0	0	0	3.8	0	0	0	0	0	0	0.3	0	0	0	0.2	0.6	0	0
Lamellodiscorbis melbyae	0	0	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rosalina sp.	0	0	0.2	78.2	2.4	77.5	0	81.7	0.3	0	36.0	0.3	0	0	0	0	0	0	0.7	0	0	0	0	2.1	0	0	0	0	0.2	1.7	0.6	1.9	3.5	0.3	0.0	0.2	2.9	16.7	5.1
E.advenum advenum	4.2	1.0	5.5	0	1.8	0	6.9	0	1.4	1.6	0.0	1.6	0	0.6	4.0	0.3	1.2	3.3	1.5	0	0	0	3.0	1.3	0	0.2	0	0	0	3.0	0.9	1.1	0	0	0	1.0	4.5	0	0
E.advenum botaniense	1.0	0	1.8	0	0.9	0	1.7	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0.2	0.9	0	0
E.advenum limbatum	0.7	0	0.2	0	1.2	0	0	0	0.3	0	0	0	0	0	0	0	0	1.1	1.1	0	0	0	4.0	3.8	0	0.2	0	0	2.2	4.7	6.2	1.9	1.1	0	0	3.1	4.9	0	0
E.crispum crispum	1.3	3.8	4.7	0	0	0	5.2	0	2.0	3.9	0	0	0	0	0	0.6	0	2.2	0	0	0	0	0	2.5	0	0	0	0	0	0	0.3	0	0	0	0	0	0.1	0	0
E.excavatum clavatum	14.7	11.9	0.8	0	27.2	0	1.7	0	10.0	7.2	0	12.9	20.5	9.0	17.7	13.0	15.7	10.9	11.2	5.9	0	0	11.4	13.8	2.1	8.1	15.2	2.6	5.1	10.6	13.7	6.7	9.3	0	0.4	9.8	12.0	0.4	5.1
E.excavatum excavatum	0.3	0	0	0	0.6	0	0	0	0	0	0	0	0	0	2.3	0	0	0	2.6	0	0	0	18.4	7.5	0	0.4	3.0	0	12.9	23.3	10.9	13.1	13.5	0	0	10.6	10.9	0	5.1
E.excavatum williamsoni	15.0	12.2	7.7	0	7.3	0	3.4	0	21.5	3.6	0.3	18.5	4.7	2.2	12.6	15.5	9.6	7.6	6.7	0	0	0	2.0	2.1	0.3	3.4	3.0	0	0	3.7	5.9	2.4	0.5	0.3	0	5.6	5.9	0.8	5.1
E.hawkesburiense	23.5	23.0	40.3	0.2	0.9	1.2	46.6	1.0	22.1	28.3	3.1	0	0	6.3	4.1	0	8.7	0	0	0	0	0	0	12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E.lene	4.6	0.7	1.0	0	7.3	0	0	0	1.6	3.3	0	6.6	7.9	0.9	2.3	7.6	2.4	1.1	13.0	2.4	0	0	1.5	5.8	2.1	3.3	9.1	0	0.2	3.7	1.9	1.9	0	0	0	1.0	3.0	0.4	0
E.macellum	1.0	0	2.0	0.2	0	0	0	0	0.3	0.3	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E.silvestri	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	o	o	o	o	o	0.1	o	o
E.advenum maorium	2.3	1.0	0.6	0	21.4	0	0	0	1.9	1.0	0.3	14.4	1.3	11.7	11.4	14.6	1.2	9.8	8.2	2.4	0.0	5.3	6.0	14.6	43.8	16.3	0	0	0.3	5.6	6.2	3.5	0.5	0	0	1.7	6.1	0	2.6
Notorotalia clathrata	0.7	0	2.4	0	0	0	0	0	2.3	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parrellina verriculata	0	0	0.6	0	0	0	0	0	0.2	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glabratella australensis	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haynesina dep. depressula	0	0.2	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0.9	0.3	0	0	0	0.0	0.4	0	0
Nonionella auris	0	0.9	2.6	0.2	0.6	0	0	0	1.9	1.0	0	0	0	0	2.3	0.3	0	2.2	0	0	0	0	0.5	0	2.1	0	0	0	0.7	0.6	0	0	0	0	0.6	0.1	0	0
Cibicidoides collinsi	0.3	0	0.4	1.1	0	0.2	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.2	0.4	0
Patellinella inconspicua	0.7	0.5	0.4	0	0.3	0	0	0	0.3	0.7	0	0.3	0	0.3	0	0.3	0	0	0.4	0	0	0	0	0.4	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0
Ammonia aoteana	5.2	8.1	6.5	0	0	0	17.2	0	6.7	5.6	2.1	1.3	3.9	1.2	5.1	0.6	7.2	3.3	1.1	1.2	3.2	0	3.0	3.3	0	0.2	0	0	0.9	4.0	2.2	1.6	4.2	0	0	8.7	4.4	1.2	0
Ammonia pustulosa	13.0	20.8	0.6	0	14.4	0	5.2	0	11.4	5.9	0	26.3	23.4	67.9	13.7	11.4	34.9	22.8	29.4	52.9	3.2	0	15.4	14.6	35.4	57.3	15.2	0	13.8	17.9	29.6	29.5	15.7	0.3	0	19.1	19.8	0.4	17.9
Aubigyna perlucida	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.5	0.4	0	0	0	0	0.8	0.3	0	3.2	0.5	0	0	0	1.5	0	0
Bolivina doniezi	0	0	0	12.9	0.3	20.8	0	14.4	0.2	0	31.5	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0.2	0.7	2.2	1.1	1.6	0	0	0	0.8	39.8	0
Bolivina pseudoplicata	0	0.5	0	0	0.3	0	0	0	0	0	0	0	0	0.3	0	0	0	1.1	0	0	0	0	0	0	0	0.2	0	0	0	1.0	0	1.3	0	0	0	0.2	0.7	0	0
Brizalina striatula	0	0	0	0	0.3	0	0	0	0	0	0	0	0.5	0	0	0	0	2.2	0	0	0	0	0.5	0.4	0	0.4	0	0	0.6	1.3	1.2	0.3	0	0	0	1.5	4.8	0
Bulimina elongata	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.5	0.8	0	0	0	0	0.3	1.0	0	0.5	0.4	0	0	0	1.1	0	0
Bulimina gibba	0.7	0	0.4	0	0.3	0	0	0	0.5	0	0	0.3	0	0.3	0.6	0	0	2.2	0.7	0	0	0	1.0	0	0	0.2	0	0	1.1	1.7	1.6	2.1	1.8	0	0	0.7	2.2	0	0
Bulimina marginata	0	0.7	0.2	0	0	0	0	0	1.2	0	0	0.0	0	0	0	0	1.2	1.1	0.7	0	0	0	0.5	0.4	0	0.2	0	0	0	1.0	0	0.5	0	0	0	0.1	0.4	0.4	0
Fursenkoina complanata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Siphogenerina raphana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	0
Spiroloxostoma croarae	0	0	0	0.2	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0	0	0	0	0	0	1.6	0
Uvigerina bassensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Favulina hexagona	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0
Heteromorphina heteromorpha	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1
Fissurina fasciata carinata	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n	n	n	n	n	n	n
Fissurina globosocaudata	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.3	0.6	0	0	0	1.1	0	0	0	0.5	0.8	0	0	0	0	0.5	2.3	0.6	1.9	0	0	0	1.0	0.9	0	0
Lagena doveyensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0
Lagena spiratiformis	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lagena sulcata peculiaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oolina ovoidea	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina austriaca	0	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	2.0	0
Guttulina pacifica	0	0	0.4	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0.2	0.8	0
Guttulina regina	0.3	1.0	0	0	0	0	0	0	0.5	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lenticulina limbosa	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaginulina cf. advena paucilocutata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella circularis	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella lakemacquariensis	0	0	0	5.1	0	0	0	0	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella pyrgoformis	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina lamarckiana	0	0	0	0	0	1.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina oblonga	0.3	0	0	0	0	0	0	0	0	0	0	0.6	1.6	0	0	0	0	0	4.1	4.1	0	0	0	2.0	2.9	0	0	0	0	0	1.4	2.3	2.2	2.7	0.9	0	0	0.8	1.3
Quinqueloculina poeyana	0	0	0.6	0	0.3	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina seminula	1.0	0.2	2.9	0	8.0	0	0	0	0.2	2.3	0	0	0	0	0	0	0	0	0.7	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1
Quinqueloculina subpolygona	0	0	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spirillina vivapara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Sample No.	44	45	46	47	48	49	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	75	76	80	81	82	83	84	85	86	87	88
Weight of sample (g)	20.0	17.5	30.0	10.0	30.0	30.0	0.7	1.5	20.0	10.0	1.5	0.3	1.1	30.0	0.7	3.0	20.0	1.0	20.0	20.0	8.7	0.4	10.2	10.0	15.2	30.0	52.0	9.1	11.5	24.8	77.9	53.3	11.6	39.8	3.8	40.9	75.5	24.3	3.0
Total number of specimens	142	192	75	165	37	202	294	414	1865	501	244	438	588	473	327	307	284	484	357	565	1767	256	1292	266	204	538	115	100	130	117	27	33	181	120	100	103	111	102	211
Abundance (spec/gm sed)	6.5	11	2.5	14.9	1.23	5.97	133	163	63.8	41.7	23.7	199	100	14.8	125	34.7	11	33.6	16.2	23.3	64	224	53.3	20.4	11.8	12.7	2.21	11	8.9	4.48	0.35	0.6	14	2.92	22	2.52	1.47	4.19	57.5
Fisher Alpha Index	2.09	2.17	2.28	3.66	3.13	4.33	1.53	6.01	2.50	3.40	2.59	1.83	1.53	2.47	1.71	8.52	2.87	1.79	1.45	1.75	1.52	1.34	1.29	1.80	1.95	1.55	2.62	2.04	1.03	1.30	1.27	2.71	1.98	1.58	2.77	0.83	3.26	3.48	0.91
% live	19.7	34.4	17.3	18.2	24.3	15.8	3.74	15.9	2.63	12.6	2.46	5.71	4.08	18.4	4.59	19.2	4.93	7.23	27.2	13.1	7.53	9.38	7.43	6.02	12.3	3.16													
% Planktic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
% Agglutinated (of benthic)	78.2	67.4	95.3	58.3	29.7	56.1	100	60	99.5	55.4	97.8	99.2	100	93.9	100	23.9	46.1	98.1	67.9	95.9	99.7	99.5	100	77.4	60.8	92.2	22.7	31	98.5	70.3	37.8	9.09	49.2	51.3	10	93.7	5.90	3.64	93.5
% Hyaline (of benthic)	6.4	27.7	2.61	40.1	70.3	42.1	0	37.1	0.54	43.1	2.05	0.23	0	5.92	0	75.9	53.6	0.32	30.4	3.72	0.06	0	0	22.6	39.2	7.81	77.3	64	1.54	24.6	55	75.8	47.5	48.7	88	2.96	88.5	94.2	1.82
% Porcellaneous (of benthic)	15.4	4.95	2.07	1.57	0	1.84	0	2.93	0	1.44	0.11	0.6	0	0.23	0	0.22	0.31	1.6	1.73	0.41	0.28	0.53	0	0	0	0	0	5	0	5.14	7.14	15.2	3.31	0	2	3.37	5.51	1.96	4.67
Hemisphaerammina bradyi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	30.8	0	0	0	0	0	0	0	0	0	0
Leptohalysis catella	0	0	1.3	0.6	0	0	3.7	3.9	4.2	0.4	10.2	5.0	0.9	0	3.7	0.7	0	8.5	0	1.9	3.7	2.3	0.1	0.4	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0
Reophax scorpiurus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0
Cuneata arctica	5.6	0	4.0	0	0	0.5	35.0	27.1	36.5	7.4	27.5	64.8	56.3	0.6	8.9	8.5	7.7	41.1	0	10.3	44.7	29.7	28.5	7.9	0	7.4	0	0	0	0	0	0	0	0	0	0	0	0	0
Ammobaculties barwonensis	59.9	63.5	42.7	52.7	21.6	54.5	34.7	18.1	28.6	30.7	25.4	2.5	10.9	84.6	74.9	8.8	33.1	25.0	68.6	71.3	15.6	24.2	24.8	45.9	54.9	18.2	3.5	8.0	0.8	36.8	40.7	8.1	45.9	36.7	5.0	80.6	6.3	3.9	86.2
Miliamina fusca	12.7	6.3	46.7	3.6	0	0.5	12.9	4.3	20.3	10.0	22.5	17.6	21.4	3.2	5.8	0.7	2.1	15.1	0.3	8.8	15.3	15.6	12.4	12.4	4.9	55.6	0	2.0	66.9	19.7	0	0	2.2	10.8	5.0	11.7	0	0	9.0
Scherochorella barwonensis	0	0	0	0	0	0	0	0	0.6	0	0	0	3.2	0	1.2	0	0	0.4	0	1.1	4.6	13.7	14.6	4.5	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0
Eggerella australis	0	0	0	0	0	0	0	0	0.1	0	0.8	0	0	0.2	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Eggerella subconica	0	0	0	0	0	0	1.4	0.2	0.2	0	0.4	0.9	1.2	0	0	0.7	0	0	0	0	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Textularia conica	0	0	1.3	1.2	0	0	0	0.2	0.3	0	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Textularia earlandi	12.0	0	1.3	0	8.1	0	9.9	5.6	7.0	6.6	9.8	6.6	5.8	4.9	3.4	2.3	2.1	8.1	0	2.3	14.0	14.1	18.7	4.1	0.5	5.4	0	0	0	0	0	0	0	0	0	0	0	0	0
Paratrochammina bartrami	0.7	0	0	0	0	0	0.7	0.5	0.5	0.6	0.4	1.6	0.2	0.4	1.2	1.0	0	0.8	0	0	0.1	0	0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Portatrochammina sorosa	0	0	0	0	0	0	1.7	1.0	0.9	0	0.8	0.5	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trochammina inflata	0	0	0	0	0	0	0	0	0.3	0.2	0	0	0	0	0	0	0.4	0.2	0	0	1.8	0	0.9	2.3	0.5	3.9	17.4	21.0	0	12.0	0	3.0	1.1	0.8	0	0	0	0	0
Buliminoides gracilis	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cibicides refulgens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	12.7	0	
Lamellodiscorbis melbyae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rosalina sp.	0	0	0	0	8.1	1.0	0	0.2	0	0.2	0	0	0	0	0	1.6	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0
E.advenum advenum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	5.4	4.9	0	
E.advenum botaniense	0	0	0	0	0	1.5	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0	
E.advenum limbatum	0	0	0	0	0	5.4	0	0.7	0	0	0	0	0	0.2	0	2.3	0.7	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	
E.crispum crispum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	4.9	0	
E.excavatum clavatum	0.7	1.0	1.3	7.3	32.4	3.5	0	1.0	0	1.0	0	0	0	0.8	0	12.1	1.1	0	6.4	0	0.1	0	0	0	4.4	0	8.7	46.0	0.8	22.2	29.6	54.5	34.8	31.7	43.0	2.9	0.9	8.8	0.5
E.excavatum excavatum	0.7	0	0	0.6	0	6.9	0	7.5	0.3	23.4	0	0.2	0	4.0	0	6.2	38.0	0	0.6	0.2	0	0	0	1.5	12.3	7.6	0	2.0	0.8	1.7	0	0	0.6	0	7.0	0	0	0	0
E.excavatum williamsoni	0	24.5	1.3	2.4	5.4	4.0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	25.2	0	0	0	18.5	0	0	0	0	0	0	0	0
E.hawkesburiense	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59.5	45.1	0	
E.lene	0	1.0	0	1.8	8.1	4.0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.9	0	
E.macellum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
E.silvestri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
E.advenum maorium	0	0	0	0.6	0	5.4	0	1.4	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.0	0	
Notorotalia clathrata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.9	0	
Parrellina verriculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0	
Glabratella australensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.0	0	
Haynesina dep. depressula	0	0.5	0	2.4	0	0	0	0	0	0.4	0	0	0	0.4	0	0	0	0	4.5	0.2	0	0	0	0	5.4	0	2.6	5.0	0	0	0	3.0	6.1	12.5	2.0	0	0	0	0
Nonionella auris	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	1.0	0	
Cibicidoides collinsi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Patellinella inconspicua	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Ammonia aoteana	5.6	1.0	0	18.2	0	2.5	0	0.7	0.2	17.4	1.2	0	0	0.2	0	28.7	6.7	0	18.8	3.4	0	0	0	21.1	16.2	0.2	33.9	11.0	0	0	11.1	12.1	5.5	1.7	31.0	0	15.3	8.8	1.4
Ammonia pustulosa	0	0.5	0	6.1	10.8	5.9	0	12.1	0.1	0	0	0	0	0	0	5.2	0	0	0	0	0	0	0	0	0	0	2.6	0	0	0	0	6.1	0.6	0	3.0	0	0	0	0
Aubignyna perlucida	0	0	0	0	0	0	0	2.7	0	0.2	0.4	0	0	0.2	0	1.3	2.5	0	0.6	0	0	0	0	0	1.0	0	0	0	0	0	0	0	0	0	1.0	0	0	0	0	0
Bolivina doniezi	0	0	0	0	5.4	0.5	0	1.7	0	0	0	0	0	0	0	1.0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bolivina pseudoplicata	0	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Brizalina striatula	0	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulimina elongata	0	0	0	0	0	0	0	1.2	0	0.4	0.4	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bulimina gibba	0	0	0	0	0	0	0	0.5	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.8	0	0
Bulimina marginata	0	0	0	0	0	0	0	1.0	0	0	0	0	0	0	0	1.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fursenkoina complanata	0	0	0	0	0	0	0	0.2	0	0	0	0	0	0	0	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Siphogenerina raphana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spiroloxostoma croarae	0	0	0	0	0	0	0	5.1	0	0	0	0	0	0	0	5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uvigerina bassensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Favulina hexagona	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heteromorphina heteromorpha	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fissurina fasciata carinata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fissurina globosocaudata	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lagena doveyensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lagena spiratiformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lagena sulcata peculiaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oolina ovoidea	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina australica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina pacifica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Guttulina regina	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lenticulina limbosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vaginulina cf. advena pauciloculata	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella circularis	8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella lakemacquariensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliolinella pyrgoformis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina lamarckiana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina oblonga	9.2	2.6	2.1	1.0	0	0	0	2.5	0	1.4	0.1	0	0	0.2	0	0.2	0.3	1.6	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9
Quinqueloculina poeyana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinqueloculina seminula	0.8	2.6	0	0.5	0	1.8	0	0.5	0	0	0	0.6	0	0	0	0	0	0	1.8	0	0.3	0.5	0	0	0	0	0	5.0	0	5.0	7.1	15.2	3.3	0	2.0	3.3	5.8	2.0	0
Quinqueloculina subpolygona	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spirillina vivapara	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Globigerina bulloides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Neogloboquadrina dutertrei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B (Part 2): Results of foraminiferal analysis of surficial sediment samples: general characteristics, and species composition (%), of each sample.

Appendix C. Species lists of the 12 foraminiferal sample associations of the modern environment - with association scores, & criteria used in their calculation (explanation in text).

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association Ap - *Ammonia pustulosa* (16 stations)						
Ammonia pustulosa	9.5625	0.56	30.62	21.49	1.00	40.34
E.advenum maorium	6.4375	0.71	11.12	8.23	1.00	24.93
E.excavatum clavatum	7.875	0.31	12.37	3.73	1.00	22.53
E.excavatum williamsoni	4.9375	0.57	6.18	2.63	0.94	17.77
E.lene	3.1875	0.73	4.09	2.63	1.00	16.27
Ammobaculties barwonensis	7.3125	0.08	11.05	-16.95	1.00	12.86
E.advenum advenum	1.25	0.60	1.56	0.76	0.81	10.50
E.excavatum excavatum	3	0.13	4.47	1.18	0.56	9.21
Ammonia aoteana	2	0.23	2.50	-2.46	0.88	8.05
E.advenum limbatum	1.1875	0.35	1.57	0.97	0.56	7.50
Bulimina gibba		0.53	0.76	0.49	0.69	7.45
Brizalina striatula	0.1875	0.48	0.51	0.30	0.56	6.65
Fissurina globosocaudata		0.50	0.55	0.41	0.56	6.61
Cibicides refulgens	0.875	0.32	1.28	0.07	0.50	6.16
Quinqueloculina oblonga	1.375	0.19	1.19	0.50	0.50	5.88
Bulimina marginata		0.37	0.35	0.21	0.50	5.19
Bolivina pseudoplicata		0.39	0.31	0.22	0.44	5.07
Neogloboquadrina dutertrei		0.36	0.14	0.11	0.38	4.47
Cuneata arctica	1.25	0.21	1.05	-5.22	0.63	4.44
Nonionella auris	0.125	0.26	0.53	0.29	0.44	4.31
Patellinella inconspicua		0.28	0.13	0.06	0.38	3.80
Globigerina bulloides		0.26	0.31	0.21	0.38	3.80
Rosalina sp.	0.25	0.19	0.79	-3.41	0.50	3.11
Bolivina doniezi	0.125	0.17	0.34	-1.41	0.38	2.67
E.hawkesburiense	1.0625	0.04	1.77	-2.41	0.25	2.61
Buliminoides gracilis		0.17	0.05	0.04	0.19	2.16
Textularia conica	0.5625	0.04	0.26	0.06	0.25	2.13
Bulimina elongata		0.12	0.21	0.10	0.25	2.10
E.crispum crispum	0.0625	0.10	0.32	-0.10	0.25	2.02
Guttulina pacifica		0.14	0.16	0.09	0.19	1.97
Textularia earlandi	0.5	-0.03	0.53	-2.02	0.50	1.93
Aubignyna perlucida	0.25	0.04	0.34	0.09	0.25	1.80
Siphogenerina raphana		0.11	0.04	0.02	0.13	1.39
E.silvestrii		0.11	0.02	0.02	0.13	1.39
Guttulina austriaca		0.09	0.09	0.03	0.13	1.29
E.advenum botaniense		0.06	0.14	0.01	0.19	1.28
Spiroloxostoma croarae		0.06	0.04	-0.12	0.13	0.96
Paratrochammina bartrami	0.0625	-0.02	0.12	-0.04	0.25	0.92
Lagena sulcata peculiaris		0.06	0.03	0.02	0.06	0.77
Favulina hexagona		0.06	0.02	0.02	0.06	0.76
Cibicidoides collinsi		0.01	0.03	-0.03	0.13	0.60
Quinqueloculina poeyana		0.03	0.02	0.00	0.06	0.50
Eggerella subconica	0.1875	-0.04	0.08	0.00	0.13	0.47
Parrellina verriculata		0.01	0.02	-0.01	0.06	0.37
Leptohalysis catella		-0.07	0.09	-0.63	0.25	0.25
Quinqueloculina seminula	0.4375	-0.17	0.59	-0.28	0.19	0.11
Notorotalia clathrata		-0.02	0.05	-0.10	0.06	0.09
E.macellum		-0.03	0.02	-0.04	0.06	-0.03
Haynesina depressula depressula		-0.09	0.10	-0.51	0.19	-0.06
Eggerella australis		-0.07	0.01	-0.06	0.06	-0.30
Portatrochammina sorosa		-0.13	0.00	-0.17	0.06	-0.85
Miliamina fusca	0.875	-0.43	1.20	-6.55	0.31	-2.70

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association Aa - *Ammonia aoteana*						
(1 station)						
Ammonia aoteana	10.00	0.31	28.66	23.70	1.00	38.69
E.excavatum clavatum	9	0.25	12.05	3.41	1.00	23.17
Cuneata arctica	7	0.55	8.47	2.20	1.00	21.19
Spiroloxostoma croarae	4.00	0.94	5.21	5.05	1.00	20.19
E.excavatum excavatum	6.00	0.55	6.19	2.89	1.00	19.21
Ammonia pustulosa	5	0.45	5.21	-3.92	1.00	14.68
E.advenum limbatum	2	0.73	2.28	1.68	1.00	13.76
Fursenkoina complanata		0.99	1.95	1.93	1.00	13.37
Brizalina striatula	1.00	0.83	1.95	1.75	1.00	13.27
Textularia earlandi	3	0.48	2.28	-0.27	1.00	12.36
Siphogenerina raphana		0.97	0.65	0.64	1.00	12.28
Uvigerina bassensis		1.00	0.33	0.32	1.00	12.25
Cibicidoides collinsi		0.90	1.30	1.25	1.00	12.14
Ammobaculties barwonenis	8	0.06	8.79	-19.20	1.00	11.84
Portatrochammina sorosa		0.84	0.98	0.80	1.00	11.44
Bulimina marginata		0.81	1.30	1.16	1.00	11.39
Eggerella subconica		0.86	0.65	0.57	1.00	11.33
Bulimina elongata		0.86	0.65	0.54	1.00	11.32
Aubignyna perlucida		0.79	1.30	1.05	1.00	11.25
E.advenum botaniense		0.87	0.33	0.20	1.00	11.17
Paratrochammina bartrami		0.74	0.98	0.82	1.00	10.61
Bolivina doniezi		0.77	0.98	-0.77	1.00	10.31
E.advenum advenum		0.68	0.98	0.18	1.00	9.89
Leptohalysis catella		0.70	0.65	-0.07	1.00	9.88
Quinqueloculina oblonga		0.66	0.21	-0.48	1.00	9.24
Rosalina sp.		0.66	1.63	-2.57	1.00	9.19
E.lene		0.58	0.33	-1.14	1.00	8.45
E.advenum maorium		0.57	0.98	-1.91	1.00	8.39
E.excavatum williamsoni		0.52	0.33	-3.23	1.00	7.27
Miliamina fusca		0.35	0.65	-7.10	1.00	4.82
Association AaEw - *Ammonia aoteana, Elphidium excavatum williamsoni*						
(1 station)						
Ammonia aoteana	10	0.31	33.91	28.95	1.00	42.68
E.excavatum williamsoni	9	0.52	25.22	21.66	1.00	36.98
Trochammina inflata	8	0.78	17.39	16.54	1.00	32.78
E.excavatum clavatum	7	0.25	8.70	0.06	1.00	18.22
Haynesina depressula depressula	5	0.75	2.61	2.00	1.00	17.81
Reophax scorpiurus	3	1.00	0.87	0.86	1.00	16.26
E.advenum limbatum	2	0.73	0.87	0.27	1.00	12.69
Ammonia pustulosa	4	0.45	2.61	-6.52	1.00	11.50
Ammobaculties barwonenis	6.00	0.06	3.48	-24.52	1.00	5.40
Association Ec - *Elphidium excavatum clavatum*						
(3 stations)						
E.excavatum clavatum	10.00	0.25	47.85	39.21	1.00	51.63
Ammonia aoteana	8.33	0.32	18.04	13.08	1.00	28.68
Quinqueloculina seminula	5.67	0.68	7.38	6.43	1.00	21.55
Haynesina depressula depressula	4.67	0.77	3.34	2.73	1.00	18.13
Trochammina inflata	4.67	0.45	8.01	7.15	0.67	17.71
E.excavatum excavatum	3.67	0.21	3.00	-0.30	0.67	10.00
Ammobaculties barwonensis	7.00	0.07	6.35	-21.64	1.00	8.80
Ammonia pustulosa	3.67	0.12	3.02	-6.11	0.67	7.40
Miliamina fusca	3.33	0.01	2.33	-5.42	0.67	6.07

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Aubignyna perlucida	0.33	0.12	0.33	0.08	0.33	2.87
E.advenum advenum	0.67	0.00	0.33	-0.46	0.33	2.13
Association Eh - *Elphidium hawkesburiense* (8 stations)						
E.hawkesburiense	10.00	0.87	36.03	31.45	1.00	48.89
Cibicides refulgens	5.75	0.84	9.86	6.85	1.00	23.36
Ammonia aoteana	6.50	0.34	9.18	4.16	1.00	19.91
E.crispum crispum	3.5	0.93	3.34	2.89	1.00	18.02
E.advenum advenum	3.75	0.74	3.88	3.04	1.00	17.12
E.excavatum williamsoni	5.125	0.29	7.93	4.32	0.75	16.36
E.excavatum clavatum	4.63	0.27	6.99	-1.62	1.00	14.28
Ammonia pustulosa	4.38	0.22	7.11	-2.00	0.75	12.51
Quinqueloculina seminula	1.50	0.62	1.80	0.92	0.88	11.33
Notorotalia clathrata	1.13	0.61	1.41	1.23	0.63	9.75
Nonionella auris	0.50	0.58	1.02	0.76	0.75	8.92
E.lene	1.00	0.36	1.75	0.28	0.75	7.98
E.advenum botaniense	0.50	0.54	0.73	0.59	0.63	7.93
Patellinella inconspicua		0.53	0.32	0.25	0.63	6.92
Globigerina bulloides		0.51	0.29	0.19	0.63	6.77
E.advenum maorium	0.63	0.35	0.97	-1.90	0.75	6.37
Guttulina regina		0.50	0.35	0.31	0.50	6.25
E.macellum	0.13	0.46	0.45	0.38	0.50	6.13
Bulimina gibba	0.50	0.26	0.41	0.14	0.50	4.89
Parrellina verriculata		0.36	0.21	0.18	0.38	4.53
Glabratella australensis		0.25	0.29	0.25	0.25	3.21
Bulimina marginata		0.19	0.27	0.12	0.38	3.17
Quinqueloculina poeyana		0.24	0.11	0.10	0.25	2.97
Guttulina pacifica		0.19	0.26	0.19	0.25	2.72
Cibicidoides collinsi		0.15	0.09	0.04	0.25	2.25
E.advenum limbatum		0.10	0.14	-0.45	0.38	2.25
Ammobaculties barwonensis	3.88	-0.07	4.37	-23.33	0.88	2.06
Quinqueloculina lamarckiana		0.13	0.22	0.19	0.13	1.66
Lamellodiscorbis melbyae		0.13	0.15	0.13	0.13	1.61
Quinqueloculina subpolygona		0.13	0.10	0.09	0.13	1.57
Fissurina fasciata carinata		0.13	0.02	0.02	0.13	1.52
Lagena spiratiformis		0.13	0.02	0.02	0.13	1.52
Oolina ovoidea		0.13	0.02	0.02	0.13	1.52
Heteromorphina heteromorpha		0.11	0.04	0.04	0.13	1.41
Lenticulina limbosa		0.11	0.02	0.02	0.13	1.40
Guttulina austriaca		0.08	0.22	0.15	0.13	1.30
E.silvestrii		0.10	0.02	0.02	0.13	1.29
Rosalina sp.	0.38	0.03	0.18	-3.97	0.38	1.01
Neogloboquadrina dutertrei		0.04	0.06	0.02	0.13	0.85
Haynesina depressula depressula		-0.01	0.05	-0.56	0.25	0.78
Bolivina pseudoplicata		0.00	0.06	-0.03	0.13	0.49
Bulimina elongata		-0.03	0.04	-0.07	0.13	0.24
Textularia conica		-0.10	0.02	-0.18	0.13	-0.38
Aubignyna perlucida		-0.10	0.04	-0.21	0.13	-0.38
Bolivina doniezi		-0.13	0.02	-1.71	0.13	-1.09
Quinqueloculina oblonga		-0.25	0.04	-0.64	0.13	-1.66
E.excavatum excavatum		-0.38	0.04	-3.22	0.13	-3.51
Textularia earlandi		-0.45	0.02	-2.50	0.13	-3.86
Miliamina fusca		-0.59	0.02	-7.63	0.13	-6.65

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association AbAp - *Ammobaculites barwonensis, Ammonia pustulosa*						
(8 stations)						
Ammobaculties barwonensis	10.00	0.07	39.06	11.06	1.00	37.30
Ammonia pustulosa	8.25	0.50	14.31	5.18	1.00	25.85
E.excavatum excavatum	6.50	0.46	8.80	5.50	0.88	20.62
E.excavatum clavatum	6.50	0.27	9.05	0.41	1.00	18.08
E.excavatum williamsoni	3.50	0.43	4.47	0.92	0.88	13.42
E.advenum maorium	3.13	0.49	3.89	1.00	0.88	13.19
E.lene	2.00	0.36	2.91	1.44	0.75	10.05
E.advenum limbatum	2.25	0.38	1.98	1.38	0.63	9.57
Miliamina fusca	2.63	0.25	2.33	-5.43	0.88	7.91
Rosalina sp.	1.63	0.31	1.24	-2.96	0.63	6.54
Ammonia aoteana	2.25	0.06	2.48	-2.48	0.75	6.51
Textularia earlandi	1.75	0.11	2.01	-0.54	0.63	6.20
Bulimina gibba	0.38	0.26	0.57	0.30	0.50	4.86
Nonionella auris		0.30	0.30	0.05	0.50	4.55
Bulimina elongata		0.25	0.27	0.16	0.38	3.64
Fissurina globosocaudata		0.23	0.24	0.09	0.38	3.49
Aubignyna perlucida	0.25	0.18	0.48	0.23	0.38	3.48
Textularia conica		0.18	0.19	-0.02	0.38	2.98
E.advenum advenum	0.50	0.05	0.53	-0.27	0.38	2.62
Bolivina doniezi		0.15	0.29	-1.46	0.38	2.33
Cuneata arctica	0.88	0.04	1.07	-5.20	0.50	2.20
E.advenum botaniense		0.12	0.21	0.08	0.25	2.09
Brizalina striatula		0.08	0.14	-0.07	0.25	1.67
Heteromorphina heteromorpha	0.13	0.11	0.01	0.00	0.13	1.54
Lagena doveyensis		0.13	0.04	0.03	0.13	1.53
Bulimina marginata		0.05	0.07	-0.07	0.25	1.41
Leptohalysis catella	0.50	-0.06	0.34	-0.37	0.25	1.12
Cibicides refulgens	0.25	0.01	0.10	-0.97	0.25	1.09
Quinqueloculina oblonga	0.63	-0.11	0.43	-0.25	0.25	1.00
E.macellum		0.04	0.08	0.02	0.13	0.86
Haynesina depressula depressula		-0.01	0.10	-0.51	0.25	0.82
Cibicidoides collinsi		0.01	0.01	-0.04	0.13	0.58
Eggerella australis		0.01	0.02	-0.06	0.13	0.58
Bolivina pseudoplicata		0.00	0.02	-0.07	0.13	0.46
Quinqueloculina seminula	0.13	-0.08	0.24	-0.63	0.25	0.42
Patellinella inconspicua		-0.03	0.04	-0.02	0.13	0.25
Eggerella subconica		-0.03	0.01	-0.07	0.13	0.23
E.crispum crispum	0.13	-0.05	0.08	-0.34	0.13	0.21
Globigerina bulloides		-0.05	0.01	-0.09	0.13	0.11
Portatrochammina sorosa		-0.05	0.01	-0.16	0.13	0.08
E.hawkesburiense	0.50	-0.10	0.51	-3.67	0.13	-0.68
Trochammina inflata		-0.12	0.01	-0.84	0.13	-0.71
Paratrochammina bartrami		-0.16	0.06	-0.10	0.13	-0.79
Association Ab - *Ammobaculites barwonensis*						
(15 stations)						
Ammobaculties barwonensis	10.00	0.08	71.47	43.48	1.00	62.00
Miliamina fusca	7.80	0.43	8.68	0.93	1.00	20.91
Ammonia aoteana	4.33	-0.03	5.94	0.97	0.67	10.54
Quinqueloculina oblonga	2.33	0.15	1.28	0.59	0.47	6.61
Haynesina depressula depressula	1.60	0.18	0.89	0.28	0.40	5.43
Textularia earlandi	2.87	-0.07	1.86	-0.69	0.47	5.32
E.excavatum clavatum	3.80	-0.11	1.81	-6.83	0.67	4.95
Cuneata arctica	2.87	-0.08	2.39	-3.88	0.40	4.24

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
E.excavatum excavatum	1.73	0.01	1.32	-1.98	0.47	3.95
Quinqueloculina seminula	1.53	0.02	0.60	-0.27	0.33	3.48
S.barwonensis	1.00	0.09	0.45	-0.13	0.20	2.87
Leptohalysis catella	0.93	-0.05	0.44	-0.28	0.27	1.88
Textularia conica	0.87	-0.02	0.30	0.09	0.20	1.82
Miliolinella circularis	0.40	0.05	0.53	0.42	0.07	1.52
Trochammina inflata	0.73	-0.04	0.23	-0.62	0.20	1.28
Aubignyna perlucida	0.53	-0.02	0.12	-0.13	0.20	1.27
Paratrochammina bartrami	0.67	-0.09	0.16	0.00	0.20	0.98
Vaginulina cf. advena pauciloculata		0.07	0.03	0.02	0.07	0.82
Eggerella australis	0.07	-0.06	0.01	-0.06	0.07	-0.15
Fissurina globosocaudata		-0.12	0.04	-0.11	0.07	-0.74
E.excavatum williamsoni	0.93	-0.44	1.79	-1.76	0.13	-1.63
E.advenum limbatum		-0.27	0.01	-0.59	0.07	-2.05
E.lene	0.47	-0.36	0.19	-1.28	0.13	-2.10
E.advenum maorium	0.53	-0.37	0.39	-2.50	0.13	-2.45
Ammonia pustulosa	1.00	-0.43	0.65	-8.48	0.20	-3.90
Association AbEc - *Elphidium excavatum clavatum, Ammobaculites barwonensis* (5 stations)						
E.excavatum clavatum	9.20	0.26	30.15	21.51	1.00	37.27
Ammobaculties barwonensis	9.80	0.07	36.33	8.33	1.00	34.96
Quinqueloculina seminula	3.60	0.30	3.20	2.33	0.60	11.26
Trochammina inflata	3.20	0.39	2.78	1.92	0.60	11.24
Haynesina depressula depressula	3.20	0.15	3.72	3.10	0.40	9.30
Miliamina fusca	4.00	-0.06	6.54	-1.21	0.60	9.23
Ammonia aoteana	4.00	-0.10	3.66	-1.30	0.60	7.60
E.excavatum williamsoni	2.40	-0.09	4.78	1.23	0.40	6.23
E.excavatum excavatum	1.60	-0.07	0.45	-2.85	0.40	2.28
Ammonia pustulosa	2.00	-0.16	2.27	-6.86	0.40	1.51
Bolivina doniezi	0.60	-0.05	1.08	-0.67	0.20	1.41
Rosalina sp.	1.20	-0.16	1.62	-2.58	0.20	0.88
E.lene	1.00	-0.24	1.62	0.15	0.20	0.86
Textularia earlandi	1.40	-0.35	1.62	-0.93	0.20	0.11
Association AbEe - *Elphidium excavatum excavatum, Ammobaculites barwonensis* (2 stations)						
E.excavatum excavatum	9.50	0.55	30.69	27.39	1.00	42.09
Ammobaculties barwonensis	9.50	0.07	31.92	3.92	1.00	31.23
Ammonia aoteana	7.50	0.32	12.03	7.06	1.00	23.08
Cuneata arctica	7.00	0.55	7.57	1.30	1.00	20.56
Miliamina fusca	5.50	0.36	6.05	-1.70	1.00	15.56
Textularia earlandi	4.00	0.49	4.35	1.80	1.00	15.18
Aubignyna perlucida	2.50	0.80	1.33	1.08	1.00	14.35
Rosalina sp.	3.00	0.67	1.51	-2.69	1.00	12.77
Quinqueloculina oblonga	2.00	0.67	0.88	0.19	1.00	12.21
Trochammina inflata		0.79	0.28	-0.58	1.00	10.25
E.excavatum clavatum	2.50	0.25	1.03	-7.61	1.00	7.02
Paratrochammina bartrami	1.00	0.24	0.30	0.14	0.50	5.27
Bulimina elongata		0.36	0.20	0.09	0.50	4.96
Brizalina striatula		0.33	0.10	-0.11	0.50	4.64
Bolivina doniezi	0.50	0.26	0.53	-1.22	0.50	4.55
Leptohalysis catella	0.50	0.20	0.20	-0.52	0.50	4.10
Bulimina gibba		0.24	0.20	-0.07	0.50	3.96
Haynesina depressula depressula		0.25	0.20	-0.41	0.50	3.96
E.advenum limbatum		0.22	0.35	-0.25	0.50	3.86

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association M - *Milliammina fusca* (4 stations)						
Miliamina fusca	10.00	0.36	56.50	48.75	1.00	59.38
Ammobaculties barwonensis	9.00	0.07	24.69	-3.30	1.00	25.15
Cuneata arctica	7.00	0.30	3.30	-2.97	0.75	14.33
Textularia earlandi	6.00	0.24	2.38	-0.18	0.75	13.08
Quinqueloculina oblonga	4.67	0.16	1.20	0.51	0.50	9.59
Textularia conica	3.33	0.30	0.46	0.26	0.50	8.66
Haplophragmoides wilberti		0.24	7.69	7.29	0.25	8.61
Trochammina inflata	3.00	0.28	1.04	0.18	0.50	8.39
Leptohalysis catella	3.00	0.20	0.43	-0.29	0.50	7.32
E.excavatum excavatum	2.67	0.04	2.10	-1.20	0.50	6.06
S.barwonensis	1.33	0.13	0.33	-0.25	0.25	3.69
E.excavatum williamsoni	1.33	0.01	0.40	-3.16	0.50	2.87
Rosalina sp.	1.00	-0.10	0.06	-4.13	0.25	0.09
E.excavatum clavatum	1.00	-0.27	0.53	-8.11	0.50	-1.33
Ammonia aoteana	0.67	-0.47	0.05	-4.92	0.25	-3.48
Ammonia pustulosa	0.33	-0.32	0.06	-9.07	0.25	-4.01
Association C - *Cuneata arctica* (10 stations)						
Cuneata arctica	10.00	0.62	39.11	32.84	1.00	48.66
Miliamina fusca	7.60	0.40	15.75	8.00	1.00	25.78
Textularia earlandi	6.90	0.54	9.94	7.39	1.00	23.37
Ammobaculties barwonensis	8.60	0.07	20.98	-7.02	1.00	21.89
Leptohalysis catella	5.40	0.79	4.25	3.54	1.00	19.84
S.barwonensis	3.20	0.54	3.72	3.14	0.60	13.21
Paratrochammina bartrami	2.00	0.72	0.48	0.32	0.90	12.10
Eggerella subconica	1.90	0.74	0.45	0.36	0.80	11.72
Portatrochammina sorosa	1.50	0.38	0.49	0.31	0.50	7.17
Eggerella australis	0.80	0.33	0.14	0.06	0.40	5.25
Trochammina inflata	1.00	0.19	0.32	-0.54	0.40	4.32
Quinqueloculina seminula	1.00	0.09	0.19	-0.68	0.40	3.40
Quinqueloculina oblonga	0.60	-0.05	0.42	-0.27	0.30	1.60
Hemisphaerammina bradyi	0.30	0.10	0.02	0.01	0.10	1.57
Spiroloxostoma croarae	0.50	0.03	0.51	0.34	0.10	1.55
Haplophragmoides wilberti	0.30	0.09	0.04	-0.36	0.10	1.34
Bulimina elongata		0.05	0.16	0.05	0.20	1.31
Lenticulina limbosa	0.10	0.09	0.03	0.03	0.10	1.22
Fursenkoina complanata		0.09	0.02	0.00	0.10	1.09
Aubignyna perlucida	0.20	-0.02	0.31	0.06	0.20	1.03
Buliminoides gracilis		0.06	0.02	0.01	0.10	0.86
Textularia conica	0.20	-0.02	0.06	-0.15	0.20	0.85
E.excavatum excavatum	0.80	-0.19	0.80	-2.50	0.30	0.23
Bolivina pseudoplicata		-0.03	0.14	0.05	0.10	0.22
Bulimina marginata		-0.12	0.10	-0.04	0.10	-0.54
Bulimina gibba		-0.19	0.05	-0.22	0.10	-1.20
Bolivina doniezi		-0.16	0.17	-1.58	0.10	-1.35
E.advenum limbatum		-0.21	0.07	-0.53	0.10	-1.41
Rosalina sp.		-0.28	0.02	-4.17	0.10	-3.18
Ammonia aoteana	0.50	-0.45	0.22	-4.75	0.30	-3.22
Ammonia pustulosa	0.80	-0.40	1.21	-7.92	0.20	-3.46
E.advenum maorium		-0.39	0.14	-2.74	0.10	-3.50
E.excavatum clavatum		-0.64	0.10	-8.54	0.20	-6.99

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association R - *Rosalina* sp. (5 stations)						
Rosalina sp.	9.80	0.69	58.03	53.78	1.00	64.06
Bolivina doniezi	9.20	0.81	23.88	22.11	1.00	39.07
Portatrochammina sorosa	5.00	0.89	1.49	1.32	1.00	18.19
Elphidium hawkesburiense	5.00	0.62	1.11	-3.13	0.80	13.64
Textularia earlandi	4.40	0.07	3.69	1.10	0.60	10.23
Cibicidoides collinsi	2.20	0.52	0.33	0.27	0.60	9.41
Miliolinella lakemacquariensis	2.20	0.40	1.50	1.41	0.40	8.55
Eggerella australis	2.20	0.30	0.80	0.72	0.40	7.25
Spiroloxostoma croarae	1.00	0.34	0.36	0.20	0.40	5.78
Textularia conica	1.80	0.19	0.62	0.41	0.40	5.70
Paratrochammina bartrami	2.00	0.14	0.28	0.12	0.40	5.25
Spirlillina	1.20	0.20	0.48	0.45	0.20	4.19
Miliolinella circularis	1.40	0.19	0.21	0.09	0.20	4.09
Guttulina austriaca	1.00	0.16	0.40	0.33	0.20	3.55
Brizalina striatula	1.40	0.02	0.96	0.75	0.20	3.29
E.macellum	0.60	0.12	0.04	-0.02	0.20	2.47
Miliolinella pyrgoformis		0.20	0.04	0.04	0.20	2.43
Guttulina pacifica		0.13	0.16	0.09	0.20	1.94
Globigerina bulloides		0.03	0.07	-0.03	0.20	1.09
Nonionella auris	0.40	-0.04	0.04	-0.21	0.20	0.94
Bulimina marginata		-0.01	0.08	-0.06	0.20	0.75
Cibicides refulgens		-0.05	0.07	-1.01	0.20	0.11
E.excavatum williamsoni		-0.10	0.23	-3.37	0.40	-0.18
Quinqueloculina oblonga		-0.16	0.15	-0.55	0.20	-0.60
Ammonia aoteana	0.60	-0.32	0.66	-4.37	0.40	-1.37
E.lene		-0.24	0.08	-1.41	0.20	-1.57
E.advenum maorium		-0.26	0.07	-2.86	0.20	-2.15
Ammonia pustulosa		-0.38	0.08	-9.17	0.20	-5.17
Miliamina fusca		-0.48	0.08	-6.90	0.20	-5.22
E.excavatum clavatum		-0.59	0.08	-8.66	0.20	-6.67
Ammobaculties barwonensis	0.40	-0.79	0.42	-27.93	0.20	-13.76

Sample No.	2	3	4	5	6	7	8	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Weight of subsample (g)	10	16	2.3	0.3	8.2	1.7	7.3	0.3	7.4	7.1	4.5	11	16	29	19	19	24	16	5	5.7	18	16	9.4	13	4.1	7.3	9.2	4.8	15	7.9	3.2	4.9	39	3.5	21	4.8	3	5.1	4.4	8.6	5.5
Total number of specimens	46	101	285	0	107	2	5	0	103	107	0	206	123	101	54	186	93	12	0	271	56	51	63	115	123	1	229	297	53	83	247	177	135	207	97	107	1	144	194	112	101
Abundance (specs/gm of sed)	4.4	6.2	127	0	13	1.2	0.7	0	14	15	0	18	7.8	3.5	2.9	10	3.9	0.8	0	45	2.9	3.1	6.7	7.9	28	0.1	24	58	3.4	11	47	29	30	50	4.7	22	0.3	26	39	13	18
Fisher Alpha Index	4.7	2.4	6.1		4.8	2	5		3.5	2.3		3.1	1.6	1.4	4.2	2.8	0.8	3.2		2.8	3.5	1	0.6	3.3	4.5	1	2.4	2.5	1.4	1.1	2.6	4.7	43	3.7	3.2	1.1	1	4.2	3.4	3.4	1.3
% live	6.5	30	12	0	31	0	40	0	33	21	0	23	20	48	22	25	49	8.3	0	26	73	75	73	21	17	100	8.7	8.4	79	45	1.6	7.3	52	17	22	45	100	19	16	0.9	34
Australocytheridea vandenboldi	2.2	7.9	6.7	0	1.9	0	20	0	14	3.7	0	2.4	3.3	0	5.6	1.6	0	17	0	0	0	0	0	0	0	0	0	0	0	1.2	1.2	0.6	07	0	0	0	0	0.7	0	0	0
Paranesidea sinusaquilensis	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0	14	0
Microceratina quadrata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0
Cytheretta robusta	0	0	1.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcytherura australis	0	0	0.4	0	0.9	0	0	0	1.9	0	0	0	0	0	1.9	0	0	0	0	2.2	5.4	0	0	5.2	2.4	0	0	0.7	0	0	0	1.1	3	0.5	1	0	0	0.7	3.1	0.9	0
Microcytherura hornibrooki	57	33	28	0	6.5	50	20	0	37	23	0	49	66	42	44	57	75	50	0	40	25	45	68	27	28	0	38	53	25	46	68	25	42	44	32	60	0	29	5.2	12	59
Microcytherura triebeli	6.5	40	1.4	0	27	0	0	0	3.9	56	0	22	23	37	11	9.7	1.1	8.3	0	4.4	20	47	27	5.2	12	100	10	8.8	45	45	6.9	10	74	14	1	17	0	4.2	5.2	0	28
Perissocytheridea conistonbayensis	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	1.9	0	0	0	0	3.7	5.4	0	0	2.6	0.8	0	2.6	1.7	0	0	2.4	1.1	22	1.4	5.2	0	0	2.8	0.5	0	0
Paracytheroma subaustralis	2.2	1	1.8	0	0.9	0	0	0	1.9	0.9	0	1	0.8	0	0	0.5	0	0	0	8.9	1.8	0	0	0	0.8	0	2.6	4.4	1.9	0	0	0	0	0.5	0	4.7	0	0.7	0	0	1
Cytheropteron sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Semicytherura sp.	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Semicytherura taylori	0	0	0	0	1.9	0	0	0	0	0	0	0.5	0	0	0	0.5	0	0	0	2.6	3.6	0	0	0.9	3.3	0	1.7	2.4	0	0	0	1.1	07	0	0	0	0	0.7	1.5	0	0
Parakrithella australis	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0.8	0	0	0	0	0	0.8	2.8	07	0.5	1	0	0	11	2.7	0
Callistocythere dorsotuberculata	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0
Callistocythere puri	0	0	5.3	0	3.7	0	20	0	4.9	0	0	4.9	0.8	4	5.6	11	0	0	0	8.9	7.1	2	0	24	9.8	0	7	4.7	0	2.4	6.5	11	3	4.3	21	0	100	18	13	0	0
Caudoleptocythere vellicata	0	0	0.7	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	07	0	1	0	0	0.7	1	0	0
Leptocythere hartmanni	2.2	0	0.4	0	0	0	0	0	0	0	0	1.9	3.3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	1
Cytheromorpha robusta	0	0	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha australis	0	0	4.2	0	1.9	50	0	0	1.9	0	0	0.5	0	0	0	0.5	0	0	0	0.4	0	0	0	3.5	2.4	0	0.4	0	0	0	0.4	4.5	3	1.9	1	0	0	0.7	12	13	0
Loxoconcha cumulus	0	0	0	0	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconha gilli	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcythere macphersoni	0	0	0	0	2.8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3.6	0	0	8.7	2.4	0	0	0	0	0	0.8	4	81	6.3	0	0	0	5.6	10	0.9	0
Osticythere baragwanathi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tasmanocypris dietmarkeyseri (?)	0	2	0	0	4.7	0	0	0	8.4	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyctenophora zealandica	6.5	0	18	0	0	0	0	0	0	0	0	0	0	0	1.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paracytherois portphillipensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	07	0.5	0	0	0	0.7	2.1	0.9	0
Paradoxostoma sp.	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paradoxostoma promunturiumphysicicolum	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sclerochilus australiensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.3	0	
Mckenzieartina portjacksonensis	6.5	6.9	12	0	0.9	0	20	0	21	3.7	0	14	3.3	16	7.4	12	22	17	0	12	23	5.9	4.8	16	12	0	14	13	26	6	9.7	15	9	14	32	5.6	0	23	12	35	9.9
Trachyleberis (?) sp.	0	1	2.5	0	3.7	0	0	0	2.9	1.9	0	0	0	0	1.1	0	0	0	0	0.7	0	0	0	0	0	0	0.9	1.3	0	0	0	0.6	0	0	0	0	0	0	0	0	0
Trachyleberis jervisbayensis	2.2	0	0.4	0	0.9	0	20	0	1	0	0	0	0	0	7.4	0.5	0	8.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trachyleberis militaris	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0.9	2.4	0	0.4	0.7	0	0	1.2	6.8	22	1	4.1	0	0	4.9	2.6	1.8	0
Australimoosella spec.133	4.3	6.9	9.1	0	0	0	0	1	0.9	0	0	0	0	0	1.9	2.2	2.2	0	0	0	0	0	0	0	0.8	0	0	0.3	0	0	0	0	0	2.4	0	0	0	0	0	0	0
Xestoleberis cedunaensis	11	2	3.9	0	41	0	0	0	8.7	0.9	0	1.9	0	0	11	3.2	0	0	0	15	5.4	0	0	5.2	21	0	23	9.8	1.9	0	1.6	11	67	7.2	1	0	0	7.6	20	5.4	1
Xestoleberis chilensis austrocontinentalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	8	0
Cytherella sp. aff lata	0	0	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Sample No.	44	45	46	47	48	49	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	75	76	78	79	80	81	82	83	84	85	86	87	88
Weight of subsample (g)	3.3	11	19	7.2	7.9	23	3.2	5	20	7.9	1.5	1.3	1.1	19	6.3	3.6	11	2.1	22	6.2	2.5	1.2	0.7	8.8	15	6.1	52	9.1	12	25	20	31	78	53	23	40	3.8	41	76	24	3
Total number of specimens	103	318	179	205	21	98	0	193	12	125	4	0	0	103	20	290	100	1	33	23	0	0	0	35	29	4	98	104	37	4	24	1	88	41	29	33	266	110	4	20	1
Abundance (specs/gm of sed)	29	11	9.3	26	2.6	3.8	0	23	0.4	13	0.4	0	0	5.1	0.8	27	7.2	0	1.3	3.1	0	0	0	3	1.7	0.5	1.9	11	2.5	0.2	0.8	0	0.6	0.7	1.1	0.8	58	2.7	0.1	0.8	0.3
Fisher Alpha Index	1.4	1.1	1.2	2.7	2.9	3.1		3.4	0.3	2.6	1.6			2.7	1	2.5	2.4	1	1.6	0.9				2.6	1.2	6	0.8	0.6	1.1	1.6	0.2	1	1.8	0.2	0.5	0.5	1.1	0.6	6	0.6	1
% live	23	6	70	13	43	33	0	1.6	8.3	11	25	0	0	21	30	1.4	24	0	52	65	0	0	0	11	17	0															
Australocytheridea vandenboldi	0	0.3	0.6	1	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	10	0	0	0	0	0	50	15	0
Paranesidea sinusaquilensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microceratina quadrata	0	0	0	0	0	0	0	0.5	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cytheretta robusta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcytherura australis	0	0	0	0	0	3.1	0	3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcytherura hornibrooki	66	68	35	43	57	4.1	0	38	0	21	50	0	0	1	25	16	0	0	9.1	0	0	0	0	8.6	10	25	58	94	11	75	0	0	77	100	66	88	62	94	25	85	100
Microcytherura triebeli	6.8	11	47	2.9	4.8	0	0	12	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Perissocytheridea conistonbayensis	0	0	0	0	0	0	0	0.5	0	0.8	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paracytheroma subaustralis	1	1.9	0	9.3	0	0	0	0	0	0	0	0	0	1	0	0	1	0	18	0	0	0	0	37	72	0	1	1	5.4	0	0	0	4.2	0	0	0	7.1	0.9	0	0	0
Cytheropteron sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Semicytherura sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Semicytherura taylori	0	0	0	2.4	0	5.1	0	2.1	0	0	0	0	0	1.9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parakrithella australis	0	0	0	0	0	3.1	0	0.5	0	2.4	0	0	0	0	0	3.1	9	0	0	0	0	0	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Callistocythere dorsotuberculata	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Callistocythere puri	1	0	0.6	7.3	4.8	47	0	1	0	12	0	0	0	27	0	7.6	17	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.1	0	0	0	0	0	0	0
Caudoleptocythere vellicata	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Leptocythere hartmanni	1	1	1.7	4.4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.9	0	0	4.8	81	25	0	100	2.1	0	34	12	23	5.5	0	0	0
Cytheromorpha robusta	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha australis	0	0	0	0	0	2	0	1	0	0.8	0	0	0	0	0	11	1	0	4.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconcha cumulus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Loxoconha gilli	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Microcythere macphersoni	0	0.3	0	2	0	6.1	0	4.7	0	7.2	0	0	0	32	0	0	3	0	4.3	0	0	0	0	5.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Osticythere baragwanathi	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3.4	0	0	0	0	0	0	0	11	10	25	0	0	2.7	0	0	0	0	0	0	0	2.3	0	0	0	0
Tasmanocypris dietmarkeyseri (?)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyctenophora zealandica	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paracytherois portphillipensis	0	0	0	1	4.8	0	0	0	0	0	0	0	0	0	0	0.7	0	0	21	0	0	0	0	2.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paradoxostoma sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paradoxostoma promunturiumphysicicolum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sclerochilus australiensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mckenzieartina portjacksonensis	24	16	15	23	14	19	0	27	100	38	50	0	0	28	45	46	58	100	39	91	0	0	0	31	0	50	0	0	0	0	0	0	4.2	0	0	0	0.8	0	25	0	0
Trachyleberis (?) sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trachyleberis jervisbayensis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trachyleberis militaris	0	0	0	2.4	0	3.1	0	1.6	0	13	0	0	0	3.9	0	3.1	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Australimoosella spec.133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Xestoleberis cedunaensis	0	0.3	0	1	0	5.1	0	6.2	0	2.4	0	0	0	3.9	0	6.2	1	0	0	0

Appendix E. Species lists of the 9 ostracod sample associations of the modern environment - with association scores, & the criteria used in their calculation (see text for explanation).

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Association LhPs - *Leptocythere hartmanni, Paracytheroma subaustralis*						
(2 stations)						
Leptocythere hartmanni	8.5	0.68	43.99	40.23	1.00	51.86
Paracytheroma subaustralis	9	0.45	38.91	35.47	1.00	46.84
Osticythere baragwanathi	7.5	0.93	6.52	5.99	1.00	25.21
Microcytherura hornibrooki	9	0.04	10.58	-31.05	1.00	9.80
Association Mp - *Mckenzieartina portjacksonensis*						
(10 stations)						
Mckenzieartina portjacksonensis	9.4	0.19	39.90	23.67	1.00	41.91
Callistocythere puri	5.7	0.12	13.62	8.06	0.70	19.15
Microcythere macphersoni	4.9	0.53	6.96	4.90	0.80	17.94
Parakrithella australis	3.3	0.51	3.39	2.66	0.70	13.20
Loxoconcha australis	3.7	0.37	4.44	3.19	0.70	13.15
Trachyleberis (Ponticocytheresis) militaris	3	0.43	3.62	2.49	0.70	12.22
Xestoleberis cedunaensis	3.7	0.12	4.41	-0.05	0.70	10.10
Paracytherois portphillipensis	1.4	0.40	2.77	2.16	0.50	8.76
Paracytheroma subaustralis	2.6	-0.20	5.73	2.29	0.40	6.34
Osticythere baragwanathi	1.50	0.24	1.58	1.05	0.30	5.93
Semicytherura taylori	1.60	0.11	0.96	0.37	0.40	4.93
Xestoleberis chilensis austrocontinentalis	0.80	0.18	1.01	0.77	0.20	3.88
Paranesidea sinusaquilensis	0.90	0.06	1.43	1.17	0.10	2.95
Microcytherura australis	0.70	-0.01	0.70	0.06	0.30	2.27
Sclerochilus australiensis	0.50	0.10	0.63	0.52	0.10	2.24
Caudoleptocythere vellicata	0.10	0.08	0.31	0.18	0.20	1.71
Microceratina quadrata	0.50	0.06	0.24	0.18	0.10	1.63
Perissocytheridea conistonbayensis	0.20	-0.01	0.17	-0.46	0.30	1.27
Cytheropteron sp.		0.10	0.03	0.03	0.10	1.22
Microcytherura hornibrooki	5.1	-0.20	7.58	-34.05	0.80	0.16
Microcytherura triebeli	0.30	-0.67	0.52	-11.20	0.10	-7.96
Association MhMp - *Microcytherura hornibrooki, Mckenzieartina portjacksonensis*						
(13 stations)						
Microcytherura hornibrooki	10	0.04	34.45	-7.18	1.00	29.22
Mckenzieartina portjacksonensis	8.54	0.20	19.32	3.09	1.00	25.33
Callistocythere puri	6.31	0.51	9.81	4.25	1.00	21.34
Xestoleberis cedunaensis	5.85	0.51	9.14	4.68	1.00	20.62
Microcytherura triebeli	6.23	0.44	8.34	-3.37	1.00	17.63
Microcytherura australis	2.85	0.69	2.04	1.40	0.85	13.67
Perissocytheridea conistonbayensis	2.31	0.69	2.18	1.55	0.85	13.13
Trachyleberis (Ponticocytheresis) militaris	1.92	0.65	2.11	0.98	0.85	12.10
Microcythere macphersoni	3.23	0.43	3.48	1.42	0.69	12.04
Semicytherura taylori	1.77	0.59	1.47	0.88	0.77	10.86
Loxoconcha australis	1.46	0.58	1.60	0.35	0.85	10.59
Parakrithella australis	0.31	0.34	0.56	-0.17	0.54	5.42
Paracytheroma subaustralis	1.69	0.06	2.04	-1.41	0.62	5.42
Trachyleberis (?) sp.	0.54	0.17	0.39	0.11	0.31	3.48
Caudoleptocythere vellicata	0.15	0.22	0.23	0.11	0.31	3.30
Australocytheridea vandenboldi	0.85	0.01	1.27	-1.05	0.38	2.83

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Paracytherois portphillipensis		0.17	0.22	-0.39	0.31	2.60
Australimoosella spec.133	0.31	0.05	0.32	-0.23	0.23	1.79
Callistocythere dorsotuberculata		0.13	0.10	0.07	0.15	1.74
Xestoleberis chilensis austrocontinentalis	0.15	0.03	0.30	0.06	0.08	0.91
Microceratina quadrata		0.03	0.04	-0.02	0.08	0.58
Paranesidea sinusaquilensis		0.03	0.04	-0.22	0.08	0.52
Tasmanocypris dietmarkeyseri (?)		0.01	0.03	-0.24	0.08	0.33
Trachyleberis jervisbayensis		-0.03	0.07	-0.14	0.08	0.02
Leptocythere hartmanni	0.54	-0.25	0.42	-3.34	0.15	-1.59
Association MhPz - *Microcytherura hornibrooki, Phyctenophora zealandica*						
(1 station)						
Phyctenophora zealandica	9.00	0.96	17.54	17.10	1.00	35.71
Australimoosella spec.133	7.00	0.82	9.12	8.57	1.00	25.75
Microcytherura hornibrooki	10.00	0.04	27.72	-13.91	1.00	24.03
Australocytheridea vandenboldi	6.00	0.63	6.67	4.35	1.00	20.58
Mckenzieartina portjacksonensis	8.00	0.16	12.28	-3.95	1.00	19.00
Loxoconcha australis	4.00	0.61	4.21	2.96	1.00	16.51
Cytheromorpha robusta	2.00	1.00	2.46	2.41	1.00	16.25
Callistocythere puri	5.00	0.40	5.26	-0.30	1.00	15.45
Trachyleberis (?) sp.	1.00	0.84	2.46	2.17	1.00	13.71
Cytheretta robusta		1.00	1.05	1.03	1.00	12.79
Xestoleberis cedunaensis	3.00	0.40	3.86	-0.60	1.00	12.34
Loxoconha gilli		1.00	0.35	0.34	1.00	12.26
Paradoxostoma sp.		1.00	0.35	0.34	1.00	12.26
Paradoxostoma promunturiumphysicicolum		1.00	0.35	0.34	1.00	12.26
Cytherella sp. aff lata		1.00	0.35	0.34	1.00	12.26
Callistocythere dorsotuberculata		0.96	0.35	0.32	1.00	11.98
Paranesidea sinusaquilensis		0.96	0.35	0.09	1.00	11.90
Caudoleptocythere vellicata		0.88	0.70	0.58	1.00	11.51
Trachyleberis jervisbayensis		0.91	0.35	0.14	1.00	11.50
Parakrithella australis		0.74	0.35	-0.38	1.00	9.93
Microcytherura australis		0.70	0.35	-0.29	1.00	9.67
Leptocythere hartmanni		0.67	0.35	-3.41	1.00	8.40
Paracytheroma subaustralis		0.44	1.75	-1.69	1.00	7.74
Microcytherura triebeli		0.35	1.40	-10.31	1.00	4.13
Association MtMh - *Microcytherura triebeli, Microcytherura hornibrooki*						
(8 stations)						
Microcytherura triebeli	9.63	0.40	43.34	31.63	1.00	47.94
Microcytherura hornibrooki	9.00	0.04	34.08	-7.55	1.00	27.70
Mckenzieartina portjacksonensis	8.00	0.18	15.61	-0.61	1.00	21.71
Australocytheridea vandenboldi	3.38	0.14	1.68	-0.64	0.50	7.70
Tasmanocypris dietmarkeyseri (?)	1.63	0.21	1.30	1.03	0.25	5.53
Callistocythere puri	3.25	-0.12	1.11	-4.45	0.50	4.00
Australimoosella spec.133	1.13	0.07	0.98	0.43	0.25	3.48
Trachyleberis (?) sp.	0.88	0.09	0.36	0.07	0.25	2.95
Leptocythere hartmanni	1.63	-0.11	0.33	-3.42	0.25	1.12
Paracytheroma subaustralis	1.75	-0.23	0.48	-2.97	0.38	1.06
Xestoleberis cedunaensis	1.50	-0.27	0.60	-3.85	0.38	0.21

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Microcythere macphersoni	0.63	-0.28	0.12	-1.94	0.13	-1.52
Association MhMtMp - *Microcytherura hornibrooki* (14 stations)						
Microcytherura hornibrooki	10.00	0.05	59.97	18.34	1.00	48.62
Microcytherura triebeli	8.21	0.45	13.61	1.90	1.00	24.09
Mckenzieartina portjacksonensis	7.79	0.20	10.58	-5.65	1.00	17.83
Australocytheridea vandenboldi	3.21	0.25	2.20	-0.12	0.57	9.10
Leptocythere hartmanni	2.93	0.20	2.80	-0.96	0.50	8.08
Paracytheroma subaustralis	3.21	0.10	1.25	-2.20	0.64	7.05
Xestoleberis cedunaensis	3.43	-0.04	2.85	-1.61	0.57	6.80
Callistocythere puri	3.43	-0.04	2.78	-2.79	0.57	6.39
*Australimoosella spec.*133	1.29	0.22	0.77	0.22	0.36	5.15
Trachyleberis jervisbayensis	0.50	0.15	0.72	0.51	0.21	3.11
Phyctenophora zealandica	0.57	0.12	0.60	0.15	0.14	2.53
Perissocytheridea conistonbayensis	0.93	-0.03	0.46	-0.17	0.29	2.15
Semicytherura sp.	0.07	0.07	0.03	0.03	0.07	0.97
Trachyleberis (?) sp.	0.36	-0.04	0.17	-0.11	0.14	0.73
Microceratina quadrata		0.03	0.03	-0.03	0.07	0.50
Semicytherura taylori	0.36	-0.13	0.24	-0.34	0.21	0.27
Paracytherois portphillipensis	0.36	-0.13	0.34	-0.27	0.07	-0.29
Caudoleptocythere vellicata		-0.09	0.03	-0.09	0.07	-0.43
Microcytherura australis	0.29	-0.22	0.18	-0.47	0.14	-0.92
Loxoconcha australis		-0.24	0.10	-1.15	0.21	-1.39
Trachyleberis (Ponticocytheresis) militaris	0.21	-0.27	0.13	-0.99	0.14	-1.56
Parakrithella australis	0.14	-0.27	0.06	-0.67	0.07	-1.89
Microcythere macphersoni	0.36	-0.29	0.08	-1.98	0.14	-1.91
Association Mh - *Microcytherura hornibrooki* (8 stations)						
Microcytherura hornibrooki	11.13	0.04	83.13	41.50	1.00	67.52
Leptocythere hartmanni	6.25	0.47	10.28	6.53	0.75	20.87
Paracytheroma subaustralis	4.00	-0.08	1.65	-1.80	0.50	6.31
Australocytheridea vandenboldi	2.13	-0.15	3.18	0.86	0.25	4.02
Osticythere baragwanathi	0.75	0.03	0.28	-0.26	0.13	1.64
Xestoleberis cedunaensis	0.88	-0.56	0.61	-3.84	0.13	-3.85
Callistocythere puri	0.75	-0.56	0.26	-5.30	0.13	-4.62
Mckenzieartina portjacksonensis	1.50	-0.69	0.61	-15.61	0.25	-7.45
Association MhAv - *Microcytherura hornibrooki, Australocytheridea vandenboldi* (1 station)						
Australocytheridea vandenboldi	9.00	0.63	39.80	37.48	1.00	49.36
Microcytherura hornibrooki	10.00	0.04	58.16	16.53	1.00	47.16
Paracytheroma subaustralis	8.00	0.44	1.02	-2.42	1.00	16.78
Xestoleberis cedunaensis	7.00	0.40	1.02	-3.43	1.00	14.98
Association XcMt - *Xestoleberis cedunaensis, Microcytherura triebeli* (1 station)						
Xestoleberis cedunaensis	10.00	0.40	41.12	36.67	1.00	49.05
Microcytherura triebeli	9.00	0.35	27.10	15.39	1.00	34.46
Tasmanocypris dietmarkeyseri (?)	7.00	0.95	4.67	4.41	1.00	23.45

Species	Dominance	Fidelity	Abundance (%)	Relative abundance	Persistence	Assoc. Score
Trachyleberis (?) sp.	5.00	0.84	3.74	3.45	1.00	19.49
Callistocythere puri	6.00	0.40	3.74	-1.83	1.00	15.49
Microcythere macphersoni	4.00	0.65	2.80	0.74	1.00	15.46
Australocytheridea vandenboldi	3.00	0.63	1.87	-0.45	1.00	13.33
Semicytherura taylori	2.00	0.70	1.87	1.28	1.00	13.25
Loxoconcha cumulus		1.00	0.93	0.92	1.00	12.71
Trachyleberis jervisbayensis		0.91	0.93	0.72	1.00	11.94
Loxoconcha australis	1.00	0.61	1.87	0.61	1.00	11.13
Microcytherura australis		0.70	0.93	0.29	1.00	10.12
Paracytheroma subaustralis		0.44	0.93	-2.51	1.00	7.12
Microcytherura hornibrooki	8.00	0.04	6.54	-35.09	1.00	5.53
Mckenzieartina portjacksonensis		0.16	0.93	-15.29	1.00	0.78

Core	Core sub-sample	Weight of sample (g)	Total number of specimens	Abundance (spec/gm sed)	Fisher Alpha Index	% Agglutinated	*Ammobaculites barwonensis*	*Ammonia aoteana*	*Aubignyna perlucida*	*Bolivina doniezi*	*Brizalina striatula*	*Cibicidoides collinsi*	*Cuneata arctica*	*E.advenum botaniense*	*E.advenum limbatum*	*E.advenum maorium*	*E.excavatum clavatum*	*E.excavatum excavatum*	*E.excavatum williamsoni*	*Eggerella subconica*	*Globigerina bulloides*	*Haplophragmoides wilberti*	*Haynesina dep. depressula*	*Leptohalysis catella*	*Miliamina fusca*	*Paratrochammina bartrami*	*Portatrochammina sorosa*	*Quinqueloculina oblonga*	*Quinqueloculina seminula*	*Rosalina sp.*	*Textularia earlandi*	*T rochammina inflata*
Samphire Island	SB1	15	103	7	0.36	100	92.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.77	0	0	0	0	0	0	0
	SB2	18	100	5.4	0.84	100	82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	6	0	0	0	0	0	0	6
	SB3	14	100	7.3	1.08	90	86	10	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0	0	1
	SB4	26	136	5.3	0.34	100	68.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31.6	0	0	0	0	0	0	0
	SB4a	26	99	3.8	1.36	96	33.3	3.03	0	0	0	0	3.03	0	0	0	0	0	0	0	1.01	0	0	0	49.5	0	0	0	0	0	10.1	0
	SB5	17	124	7.2	1.29	66.9	62.1	25.8	0	0	0	0	0	0	0	0	2.42	4.84	0	0	0	0	0	0	1.61	0	0	0	0	0	0	3.23
	SB6	14	105	7.4	1.08	53.3	51.4	41	0	0	0	0	0	0	0	0	4.76	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	1.9
	SB6a	15	97	6.7	0.59	87.6	83.5	12.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.12
	SB7	18	103	5.7	1.67	18.4	15.5	78.6	0	0	0	0	0	0	0	0	0.97	1.94	0	0	0	0.97	0	0	0.97	0	0	0	0	0	0	0.97
	SB8	11	117	11	1.21	16.2	15.4	83.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.85
	SB8a	11	120	11	0.79	35.8	35.8	60.8	0	0	0	0	0	0	0	0	2.5	0.83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SB9	15	97	6.4	1.08	41.2	39.2	56.7	0	0	0	0	0	1.03	0	0	1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.06
	SB10	18	103	5.9	0.83	49.5	42.7	50.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.97	0	0	0	0	0	0	0	0	0	5.83
	SB10a	27	109	4	1.09	45.9	40.4	53.2	0	0	0	0	0	0	0	0	0	0.92	0	0	0	0	1.83	0	0	0	0	0	0	0	0	0	3.67
	SB11	46	62	1.4	0.94	90.3	83.9	9.68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.61	0	0	0	0	0	0	0	0	0	4.84
Stinking Point	LEB1	57	83	1.4	1.8	55.4	22.9	2.41	0	0	0	0	0	0	0	0	34.9	2.41	0	0	0	0	0	4.82	0	4.82	0	0	0	0	0	0	27.7
	LEB1A	26	96	3.7	2.06	35.4	12.5	5.21	0	0	0	0	0	0	0	0	45.8	6.25	0	0	0	0	6.25	0	6.25	0	0	0	1.04	0	0	16.7
	LEB2	52	95	1.8	1.72	83.2	41.1	2.11	0	0	0	0	0	0	0	0	11.6	3.16	0	0	0	1.05	0	0	8.42	0	0	0	0	0	0	32.6
	LEB2A	28	107	3.8	1.34	29	19.6	22.4	0	0	0	0	0	0	0	0	43.9	4.67	0	0	0	0	0	0	0.93	0	0	0	0	0	0	8.41
	LEB3	38	108	2.8	1.33	26.9	24.1	42.6	0	0	0	0	0	0	0	0	26.9	3.7	0	0	0	0	0	0	0.93	0	0	0	0	0	0	1.85
	LEB3A	31	106	3.5	1.34	33	31.1	40.6	0	0	0	0	0	0	0	0	20.8	4.72	0	0	0	0	0	0	0	0	0	0	0.94	0	0	1.89
	LEB4	43	111	2.6	1.09	9.91	9.01	86.5	0	0	0	0	0	0	0	0	2.7	0.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9
	LEB5	10	107	10	0.82	5.61	5.61	89.7	0	0	0	0	0	0	0	0	1.87	2.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LEB6	14	105	7.6	0.81	1.9	1.9	96.2	0	0	0	0	0	0	0	0	0.95	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	LEB7	28	115	4	0.8	0.87	0	96.5	0	0	0	0	0	0	0	0	1.74	0.87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.87
Duckhole Rivulet	DB1	5.3	102	19	3.1	48	43.1	23.5	1.96	0	0	0	2.94	0	0.98	0	0	13.7	0	0	0	0	0	0.98	2.94	0	0	6.86	0.98	0	0	1.96
	DB2	8.8	118	13	2.54	48.3	44.1	36.4	3.39	0	0	0	0.85	0	0	0	0	7.63	0	0	0	1.69	0.85	0	2.54	0	0	1.69	0.85	0	0	0
	DB2A	9.4	118	13	2.98	33.9	29.7	33.9	6.78	0	0	0	1.69	0	0.85	0	0	18.6	0	0	0	0	0	2.54	3.39	0	0	0.85	0	0	0.85	0.85
	DB3	10	140	14	2.13	31.4	30	43.6	3.57	0	0	0	3.57	0	1.43	0	0	15	0	0	0	1.43	0	0.71	0	0	0	0.71	0	0	0	0
	DB4	4.6	144	31	1.51	38.2	36.8	47.2	0	0	0	0	0	0	2.78	0	4.17	6.94	0	0	0	0	0	0.69	1.39	0	0	0	0	0	0	0
	DB5	3	126	42	2.83	31.7	27	49.2	0	0	0	0.79	0	0	3.17	0	5.56	7.14	0.79	0	0	0	0	0.79	3.17	0.79	0	1.59	0	0	0	0
	DB6	3.6	124	35	1.6	24.2	22.6	61.3	0	0.81	0	0	0	0	1.61	0	11.3	0	0	0	0	0	0	0	0	0.81	0	1.61	0	0	0	0
Midway Bay	PW1	4.9	534	109	0.95	100	14.2	0	0	0	0	0	50.6	0	0	0	0	0	0	0.19	0	0	0	0	26.6	0	0	0	0	0.37	8.05	0
	PW2	4.4	167	38	0.97	100	10.2	0	0	0	0	0	50.3	0	0	0	0	0	0	0	0	0	0	0	35.3	0	0.6	0	0	0	3.59	0
	PW3	6	605	101	0.78	100	10.7	0	0	0	0	0	42	0	0	0	0	0	0	0	0	0	0	0	35.4	0.17	0	0	0	0	11.7	0
	PW4	2.9	459	156	0.98	100	8.93	0	0	0	0	0	54.2	0	0	0	0	0	0	0	0	0	0	0	28.5	0.44	0.44	0	0	0	7.41	0
	PW5	6.3	607	96	0.95	100	14.5	0	0	0	0	0	60.5	0	0	0	0	0	0	0	0	0	0	0.66	15	0.82	0	0	0	0	8.57	0
	PW6	8.2	693	84	1.1	100	18	0	0	0	0	0	60.8	0	0	0	0	0	0	0.14	0	0	0	0.43	15.2	0.14	0	0	0	0	5.34	0
	PW7	7.7	422	55	1.2	100	19.9	0	0	0	0	0	56.6	0	0	0	0	0	0	0.71	0	0	0	0	15.6	0.95	0.47	0	0	0	5.69	0
	PW8	11	545	49	1.15	100	14.3	0	0	0	0	0	62.4	0	0	0	0	0	0	0.73	0	0	0	0.18	15.6	0.18	0	0	0	0	6.61	0
	PW9	9.8	426	44	1.2	100	16.7	0	0	0	0	0	50.2	0	0	0	0	0	0	0.7	0	0	0	1.88	23	0	1.64	0	0	0	5.87	0
	PW10	12	239	20	1.35	100	28	0	0	0	0	0	33.9	0	0	0	0	0	0	1.26	0	0	0	1.26	24.7	2.09	0	0	0	0	8.79	0
	PW11	10	217	22	1.38	100	29	0	0	0	0	0	40.6	0	0	0	0	0	0	1.38	0	0	0	0	21.2	0	0.46	0	0	0	6.91	0.46
	PW12	8.1	74	9.1	1.87	100	24.3	0	0	0	0	0	31.1	0	0	0	0	0	0	2.7	0	0	0	0	27	1.35	1.35	0	0	0	12.2	0
	PW13	11	42	3.8	2.4	100	26.2	0	0	0	0	0	19	0	0	0	0	0	0	7.14	0	0	0	0	21.4	4.76	14.3	0	0	0	7.14	0
	PW14	24	155	6.4	1.25	100	32.9	0	0	0	0	0	34.8	0	0	0	0	0	0	0	0	0	0	0	15.5	1.29	6.45	0	0	0	9.03	0
	PW15	10	170	17	1.46	100	54.1	0	0	0	0	0	26.5	0	0	0	0	0	0	1.18	0	0	0	0	11.2	2.35	1.18	0	0	0	3.53	0
	PW16	12	175	14	1.2	100	48.6	0	0	0	0	0	27.4	0	0	0	0	0	0	0.57	0	0	0	0	20	0.57	0	0	0	0	2.86	0
	PW17	10	407	41	1.43	100	44.2	0	0	0	0	0	34.2	0	0	0	0	0	0	2.7	0	0	0	1.72	11.3	0.25	0.74	0	0	0	4.91	0
	PW18	13	115	8.7	1.31	100	60	0	0	0	0	0	24.3	0	0	0	0	0	0	0.87	0	0	0	0	8.7	0	3.48	0	0	0	2.61	0
	PW19	20	45	2.2	1.43	100	60	0	0	0	0	0	22.2	0	0	0	0	0	0	0	0	0	0	0	13.3	2.22	2.22	0	0	0	0	0
	PW20	16	220	14	1.62	100	56.4	0	0	0	0	0	19.5	0	0	0	0	0	0	0.45	0	0	0	0.45	16.4	0.45	1.82	0	0	0	4.55	0
	PW21	15	134	8.7	1.53	100	56	0	0	0	0	0	8.96	0	0	0	0	0	0	3.73	0	0	0	0.75	26.9	1.49	0	0	0	0	2.24	0
	PW22	15	80	5.5	1.15	100	81.3	0	0	0	0	0	8.75	0	0	0	0	0	0	1.25	0	0	0	0	6.25	2.5	0	0	0	0	0	0
	PW23	18	78	4.3	1.19	100	76.9	0	0	0	0	0	5.13	0	0	0	0	0	0	0	0	0	0	0	7.69	0	6.41	0	0	0	3.85	0

Appendix F. Results of foraminiferal analysis of core sediment sub-samples: general characteristics, and species composition (%), of each sample.

Species	Dominance	Fidelity	Abundance (%)	Rel.abundance	Persistence	Assoc. Score
Association AaAb - *Ammobaculites barwonensis, Ammonia aoteana*						
Ammonia aoteana	10.00	0.42	49.05	37.02	1.00	52.77
Ammobaculties barwonensis	8.91	0.05	32.67	-0.55	1.00	29.27
E.excavatum excavatum	5.36	0.33	5.26	2.57	0.73	15.09
E.excavatum clavatum	4.91	0.07	6.56	-0.01	0.64	11.87
Trochammina inflata	3.27	0.28	1.47	0.05	0.55	8.99
E.advenum limbatum	2.45	0.27	0.89	0.47	0.45	7.43
Haplophragmoides wilberti	1.64	0.21	0.38	0.03	0.27	4.91
Quinqueloculina oblonga	1.27	0.13	0.43	-0.07	0.36	4.17
Leptohalysis catella	1.27	0.10	0.43	-0.07	0.36	3.98
Aubignyna perlucida	1.27	0.02	0.94	0.67	0.18	3.08
Bolivina doniezi	0.45	-0.06	0.07	-0.92	0.09	0.18
Paratrochammina bartrami	0.45	-0.14	0.15	-0.20	0.18	0.14
Quinqueloculina seminula	0.45	-0.15	0.09	-0.48	0.09	-0.37
Miliamina fusca	1.91	-0.35	0.81	-8.06	0.36	-1.24
E.excavatum williamsoni	0.27	-0.21	0.07	-1.94	0.09	-1.57
Cuneata arctica	0.91	-0.33	0.48	-9.33	0.18	-3.60
Textularia earlandi	0.09	-0.43	0.08	-2.48	0.09	-3.72
Association Aa(Ab) - *Ammobaculites barwonensis, (Ammonia aoteana)*						
Ammonia aoteana	10.00	0.40	88.55	76.53	1.00	82.66
E.excavatum excavatum	6.33	0.42	1.24	-1.45	0.83	14.41
E.excavatum clavatum	6.50	0.27	1.37	-5.20	0.83	12.26
Trochammina inflata	4.17	0.39	0.60	-0.82	0.67	10.82
Ammobaculties barwonensis	7.50	-0.13	7.91	-25.31	0.83	6.68
Haplophragmoides wilberti	1.00	0.09	0.16	-0.19	0.17	2.60
Miliamina fusca	0.83	-0.54	0.16	-8.71	0.17	-5.35

Appendix G. Species lists of foraminiferal sample associations found only in the short cores - with association scores, and the criteria used in their calculation (see text for explanation).

Core	Core sub-sample	Weight of sample (g)	Total number of specimens	Abundance (spec/gm sed)	Fisher Alpha Index	*Australocytheridea vandenboldi*	*Callistocythere puri*	*Cytheropteron sp.*	*Leptocythere hartmanni*	*Loxoconcha australis*	*Mckenzieartina porijacksonensis*	*Microceratina quadrata*	*Microcythere macphersoni*	*Microcytherura hornibrooki*	*Osticythere baragwanathi*	*Paracytherois portphillipensis*	*Paracytheroma subaustralis*	*Parakrithella australis*	*Semicytherura taylori*	*Xestoleberis cedunaensis*	*Xestoleberis chilensis austrocontinentalis*
Duckhole Rivulet	DB1	80	80	2.38	1.49	0	2.5	0	0	0	80	0	0	2.5	8.8	2.5	3.75	0	0	0	0
	DB2	57	57	1.11	2.1	0	0	0	1.8	8.8	45.6	3.51	0	3.51	5.3	32	0	0	0	0	0
	DB2A	54	54	1.21	3.6	0	5.56	0	11	3.7	57.4	0	1.85	5.56	1.9	1.9	9.26	1.9	0	0	0
	DB3	63	63	1.31	4.31	0	1.59	1.6	6.3	11	25.4	1.59	0	6.35	22	4.8	14.3	3.2	0	1.6	0
	DB4	103	103	11.2	3.49	0	6.8	0	8.7	15	23.3	0	2.91	11.7	15	0	6.8	2.9	0.97	5.8	1
	DB5	99	99	16.9	4	0	7.07	1	3	5.1	36.4	0	1.01	12.1	7.1	1	11.1	7.1	0	7.1	1
	DB6	93	93	11.8	4.08	1.1	3.23	1.1	11	3.2	33.3	0	1.08	10.8	5.4	0	12.9	9.7	0	6.5	1.1
Stinking Point	LEB2A	28	84	2.98	1.13	0	0	0	21	0	3.57	0	0	70.2	3.6	0	1.19	0	0	0	0
	LEB3	38	84	2.19	1.13	0	0	0	6	0	1.19	0	0	89.3	0	0	2.38	0	0	1.2	0
	LEB3A	31	117	3.81	1.9	0	0	0	23	0	5.13	0	0	52.1	5.1	1.7	11.1	0	0.85	0.9	0
	LEB4	43	73	1.7	2.69	0	0	0	27	0	2.74	0	0	30.1	18	1.4	16.4	1.4	1.37	1.4	0
	LEB5	10	75	7.24	2.16	0	0	0	21	1.3	1.33	0	0	41.3	6.7	0	21.3	0	2.67	4	0
	LEB6	14	76	5.48	1.5	0	0	0	24	0	1.32	0	0	23.7	20	0	28.9	0	2.63	0	0
	LEB7	28	39	1.37	1.97	0	2.56	0	33	0	0	0	0	35.9	21	0	5.13	0	0	2.6	0
Samphire Island	SB5	43	50	1.16	1.24	0	0	0	26	0	0	0	0	46	18	0	10	0	0	0	0
	SB6	27	62	2.33	1.56	1.6	1.61	0	26	0	0	0	0	59.7	6.5	1.6	3.23	0	0	0	0
	SB7	51	37	0.73	0.91	0	0	0	22	0	0	0	0	67.6	2.7	0	8.11	0	0	0	0

Appendix H. Results of ostracod analysis of core sediment sub-samples: general characteristics, and species composition (%), of each sample.

APPENDIX I. Systematic description of Foraminifera & Ostracoda.

Below are listed the species of Foraminiferida and Ostracoda identified in the Pitt Water Estuary. Brief notes are provided only of those species which presented problems for identification (including those identified only down to genus level), or which displayed significant variation in form.

For the foraminifera, the classification scheme of Loeblich and Tappan (1987) was used, with additional taxonomic references including: Yassini and Jones (1995), Albani et al. (2001), Albani (1979), Brady (1884), Chapman and Parr (1937), and Hayward et al. (1997, 1999). For the complex family Elphiididae, the classification scheme of Hayward's monograph (1997), in conjunction with Albani et al. (2001), used.

For the Ostracoda, the taxonomic scheme of Van Morkhoven (1962) was used, with additional taxonomic references including: Yassini and Jones (1995), Hartmann (1978, 1979, 1980, 1981), Yassini and Jones (1987), McKenzie (1967), McKenzie et al. (1990), and Yassini and Wright (1988).

PHYLUM SARCOMASTIGOPHORA

Subphylum SARCODINA Schmarda, 1871

Superclass RHIZOPODEA von Siebold, 1845

Class GRANULORETICULOSEA

Subclass LOBOSIA Carpenter, 1861

Order FORAMINIFERIDA Eichwald, 1830

Suborder TEXTULARIINA Delage & Herouard, 1896

Superfamily ASTORHIZACEA Brady, 1889

Family HEMISPHAERAMMINIDAE Loeblich & Tappan, 1961

Genus *Hemisphaerammina* Loeblich & Tappan, 1957

Hemisphaerammina bradyi Loeblich & Tappan, 1957

Superfamily LITUOLACEA de Blainville, 1827

Family HAPLOPHRAGMOIDIDAE Maync, 1952

Genus *Haplophragmoides* Cushman, 1910

Haplophragmoides wilberti Anderson, 1953 (Plate 1, Fig. A)

Family HORMOSINIDAE Haeckel, 1894

Genus *Leptohalysis* Loeblich & Tappan, 1984

Leptohalysis catella (Hoeglund, 1947) (Plate 1, Fig. B)

Genus *Reophax* de Montfort, 1808

Reophax scorpiurus de Montfort, 1808

Genus *Cuneata* Fursenko, 1979

Cuneata arctica (Brady, 1881) (Plate 1, Fig. C)

Synonymy:

Reophax arctica Brady, 1881, p. 405; Hayward and Hollis, 1994, p.200, pl. 1, Figs. 6-10; Hayward and Triggs, 1994, pl. 1, Fig. 15.

Reophax cylindricus Wells, 1985, p. 580, Figs. 5a-c, 7g,h,k.

Reophax sp.; Yassini and Jones, 1989, p. 255, Fig. 10, nos. 10-11.

Cuneata arctica Loeblich and Tappan, 1988, p. 59, pl. 45, Figs. 7-9; Yassini and Jones, 1995, p. 69, Figs. 40-42; Hayward et al., 1999, p. 82, pl. 1, Figs. 11-12; Albani et al., 2001 (CD-ROM).

Description:

The species represents a variety of forms characterised by a slender, elongate, uniserial, finely-agglutinated test. The initial chambers increase significantly in width, with the width of subsequent chambers more uniform. The final chamber tapers to a slit-shaped, terminal aperture. However, some forms exist in which the final chamber narrows less towards the aperture, with the latter being more oval in shape. Sutures are distinct.

Remarks:

Reophax sp. of Yassini and Jones (1989) is tentatively assigned to *Cuneata arctica*. Although a description of the species was not provided, illustrations of the species are very similar to *Cuneata arctica*.

Martinotiella cf. *communis* of Apthorpe (1980), although very similar in form and habitat to *Cuneata arctica*, is not assigned to it, as the latter does not feature an early short trochospiral/triserial stage followed by two biserial chambers.

Subfamily REOPHACINAE Cushman, 1910

Genus *Scherochorella* Loeblich and Tappan, 1984

Scherochorella barwonensis (Collins, 1974) (Plate 1, Fig. D)

Synonymy:

Protoschista findens Yassini and Jones, 1989, Figs. 10.10, 10.11; Yassini and Jones, 1995, p. 69, Figs. 39, 43.

Reophax barwonensis Collins, 1974, p. 8, pl. 1, Fig 1; Apthorpe, 1980, pl. 29, Fig. 7; Bell and Dury, 1992, p. 12, Fig. 4.5; Bell, 1995, p. 229, Fig. 2.1; Bell, 1996, p. 5, pl. 1, Fig. a; Cann et al. 2000, pl. 1. Figs. a,b.

Scherochorella barwonensis (Collins): Strotz, 2003, p. 166, pl. 1, Figs. 1-3.

Description:

The species is elongate, uniserial, and agglutinated, with a round, terminal aperture. The species differs from *C.arctica* by having a different aperture, a proloculus, and by having chambers of more even width. It varies in morphology, mainly (as similarly observed by Strotz, 2003) by the total number of chambers, coarseness of test, and size of the initial chamber relative to the later chambers.

Remarks:

The author agrees with Strotz (2003) that this species belongs to the genus *Scherochorella*, rather than *Reophax*, based upon its subglobular proloculus, appressed chambers and depressed sutures. The author also agrees with Strotz (2003) that *Protoschista findens* of Yassini and Jones (1989, 1995) is actually misidentified *S.barwonensis*. Consequently, the distribution of *S.barwonensis* can be extended from the south coast of New South Wales to the south-east coast of Tasmania.

Hayward and Hollis (1994) placed *S.barwonensis* in synonymy with *Reophax moniliforme*. Bell (1996) rejected this synonymy, by pointing out that *barwonensis* has a more robust test is more agglutinated, and is an estuarine or well protected marine lagoonal species; whereas, *R.moniliforme* is fragile, more finely agglutinated, and an open ocean shelf species.

Family LITUOLIDAE Blainville, 1827

Genus *Ammobaculites* Cushman, 1910

Ammobaculties barwonensis Collins, 1974 (Plate 1, Figs. E-G)

Synonymy:

Ammobaculites? *barwonensis* Collins, 1974, p.9; pl. 1, Figs. 3a-b.

Ammobaculites barwonensis (Collins): Apthorpe, 1980, p. 225; pl. 28, Figs. 4, 5, 10-13; Bell, 1996, pl. 1, Fig. K; Cann et al., 2000b, pl. 1, Fig. c-e.

Description:

This is a relatively large species, ranging in length from 1 to 2 mm. Sutures are often distinct, and the wall structure finely agglutinated (although some coarser-grained specimens were observed). The species is characterised by an early close coiled section (usually the widest part of the test) followed by a uniserial, straight section.

The form and characteristics of this species in the study area match exactly the description and illustrations provided by Apthorpe (1980) for the species in the Gippsland Lakes System, Victoria. Apthorpe (1980) described the species as displaying considerable variation in form, mainly in shape and the degree of compression. In the current study, the species displays such variation, mainly in shape, with a continous range in forms between those with an early coiled portion only slightly wider than that of the later, uncoiled portion, and those with an early coiled portion 1.5 times wider than the uncoiled portion. Most specimens display slight compression, although a minority display significant compression. Flabelliform specimens, although rare, also occur, as noted by Apthorpe (1980).

Remarks:

New Zealand specimens of *A.exiguus*, illustrated in Hayward et al. (1994, 1999), display considerable morphological similarities to that of *A.barwonensis* in the current study. A preference by *A.barwonensis* for a black mineral forming part of the wall structure, was similarly observed by Hayward et al. (1994) for *A.exiguus* in New Zealand.

In the study area, specimens of A.barwonensis with an early, coiled portion considerably wider than the later, straight portion, display morphological similarities to Australian specimens of *A.exiguus* (in Strotz, 2003; Cotter, 1996; and Bell, 1996) and *A.agglutinans* (in Yassini and Jones, 1989, 1995). Consequently, it is possible that the identification of *A.barwonensis* in the current study may include some specimens of these species. However, the continuous range of different forms of *A.barwonensis* in the current study allows no separation into different morphotypes, such that *A.exiguus* or *A.agglutinans* cannot be identified in the study area as discrete species. Essentially, it is this continuous range in form of specimens of *Ammobaculties* within the estuary which best identifies them as *A.barwonensis*.

Also, as a large number of specimens of *A.barwonensis* were broken, it is possible that some *Haplophragmoides australensis* may have been misidentified as broken early portions of *A.barwonensis*.

Family RZEHAKINIDAE Cushman, 1933
Genus *Miliammina* Heron-Allen & Earland, 1930
Miliammina fusca (Brady, 1870) (Plate 1, Fig. H)

Superfamily TEXTULARIACEA Ehrenberg, 1838
Family EGGERELLIDAE Cushman, 1937
Genus *Eggerella* Cushman, 1935
Eggerella australis Collins, 1958 (Plate 1, Fig. I)
Eggerella subconica Parr, 1950

Family TEXTULARIIDAE Ehrenberg, 1838
Genus *Textularia* Defrance, 1824
Textularia conica d'Orbigny, 1839 (Plate 1, Fig. J)
Textularia earlandi Parker, 1933 (Plate 1, Fig. K)

Superfamily TROCHAMMINACEA Schwager, 1877
Family TROCHAMMINIDAE Schwager, 1877
Genus *Paratrochammina* Bronnimann, 1979 emend. Bronnimann & Whittaker, 1988
Paratrochammina bartrami (Hedley, Hurdle & Burdett, 1967) (Plate 1, Figs. L-M)

Genus *Portatrochammina* Echols, 1971
Portatrochammina sorosa (Parr, 1950) (Plate 1, Figs. N-O)

Genus *Trochammina* Parker & Jones, 1859
Trochammina inflata (Montagu, 1808) (Plate 1, Figs. P-Q)

Suborder ROTALIINA Delage & Herouard, 1896
Superfamily Rotaliacea Ehrenberg, 1839
Family BULIMINOIDIDAE Seiglie, 1970

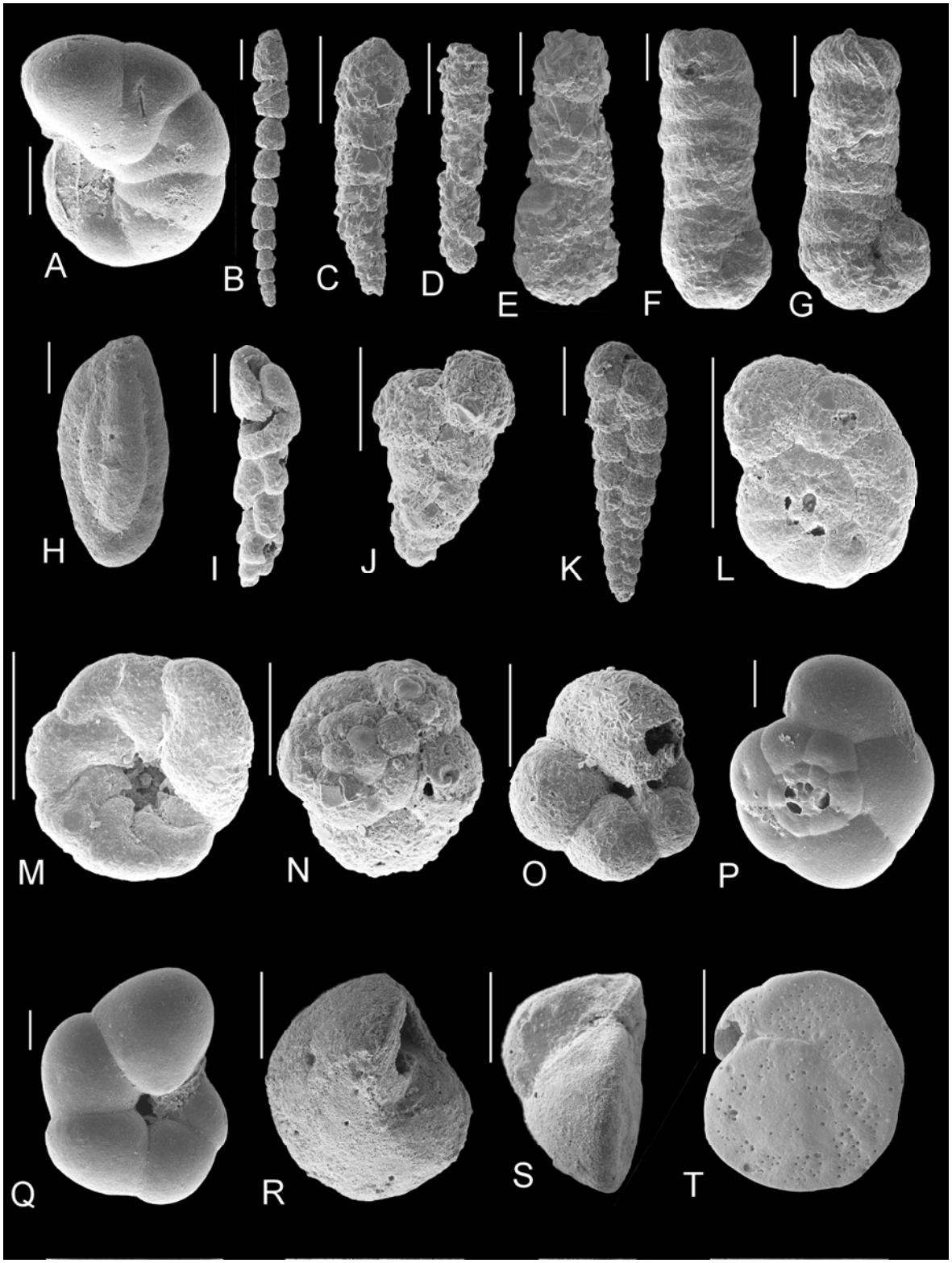

Plate 1: (All scale bars = 100 um) - **A**, *Haplophragmoides wilberti*; **B**, *Leptohalysis catella*; **C**, *Cuneata arctica*; **D**, *Scherochorella barwonensis*; **E-G**, *Ammobaculites barwonensis*; **H**, *Miliammina fusca*; **I**, *Eggerella australis*; **J**, *Textularia concia*; **K**, *Textularia earlandi*; **L-M**, *Paratrochammina bartrami*; **N-O**, *Portatrochammina sorosa*; **P-Q**, *Trochammina inflata*; **R-T**, *Cibicides refulgens*.

Genus *Buliminoides* Cushman, 1911

Buliminoides gracilis (Collins, 1953)

Family CIBICIDIDAE Cushman, 1927

Genus *Cibicides* de Montfort, 1808

Cibicides refulgens de Montfort, 1808 (Plate 1, Figs. R-T)

Family DISCORBIDAE Ehrenberg, 1838

Genus *Lamellodiscorbis* (see Loeblich & Tappan, 1987)

Lamellodiscorbis melbyae Hansen & Revets, 1992

Family ROSALINIDAE Reiss, 1963

Genus *Rosalina* d'Orbigny, 1826 (Plate 2, Figs. A-B)

Rosalina sp.

Description:

Test low trochospiral, plano-convex, small, with a rounded periphery. The dorsal side is convex, and the ventral side is flat to slightly concave. Aperture is interiomarginal umbilical, with the umbilicus being deep and distinct. Chambers crescentic in shape and increase in size, with the final chamber being the largest and overlapping chambers of previous whorl. Wall calcareous, coarsely perforated on both sides, although less so on the ventral side, where it is absent from the periphery. On the dorsal side, the central portion of the test is smooth, with only the chambers of the last whorl being perforated. Test often translucent and thin, frequently tinged brown.

Remarks:

The author has assigned this species to the genus *Rosalina* based upon the presence of characteristics typical of the genus, such as the low trochospiral and planoconvex chamber arrangement, and the presence of perforations. Within the genus, *Rosalina*, *Rosalina* sp. is most similar to *Rosalina bradyi* and *Rosalina australis*. However, it differs from both these species by the spiral side having a broad, smooth central portion, and by the surrounding portion being less densely perforated. Additionally, on the umbilical side, *R.australis* is (unlike *Rosalina* sp.) imperforate, and *R.bradyi* is more densely perforated.

Rosalina sp. also displays significant similarities to *Gavelinopsis praegeri*, particularly by the latter species featuring coarse perforations on both the spiral and umbilical sides, a

smooth central area on the spiral side, and by the test being translucent and brown-tinged. However, typical specimens of *G.praegeri* illustrated in Albani et al. (2001), Hayward et al. (1999) and Hayward et al. (1994), differ from *Rosalina* sp. by having a very broad smooth central area on the spiral side, and by the umbilical side being flatter with a less distinct umbilicus, and a sharper, more lobulate outline. However, it is worth noting that in Loeblich and Tappan (1994), the range of specimens of the species illustrated, displays variation in the size of the smooth central spiral area, ranging from very broad to very small, and therefore, include intermediate forms which have a moderately-sized smooth central area very similar to that of *Rosalina* sp.

Family ELPHIDIIDAE Galloway, 1933

For the complex family, Elphiididae, Hayward et al. (1997) and Albani et al. (2001) were used for classification and identification. For a full description of each species, including synonymy, see Hayward et al. (1997).

Subfamily ELPHIDIINAE Galloway, 1933

Genus *Elphidium* de Montfort, 1808
Elphidium advenum (Cushman, 1922)
Elphidium advenum advenum (Cushman, 1922) (Plate 2, Fig. C)

Synonymy:

See Hayward et al., 1997.

Description:

See Hayward et al., 1997.

Remarks:

Specimens of *E.advenum advenum* displayed variation within the umbilical region, with either the central boss being smooth, broad and pitted, or smaller, glassy, and surrounded by a circular ring which joins the chamber ends. Although this variation in umbilical region may suggest the presence of two different morphotypes of the species, such could not be differentiated due to the range of intermediate forms, and identical environmental

distribution of all variants. An additional observation was that specimens with a broader boss, had more inflated chambers and a test which was more compressed.

Elphidium advenum botaniense Albani, 1981 (Plate 2, Fig. D)
Elphidium advenum limbatum (Chapman, 1907) (Plate 2, Fig. E)
Elphidium advenum maorium Hayward 1997 (Plate 2, Fig. F)
Elphidium crispum (Linne, 1758)
Elphidium crispum crispum (Linne, 1758) (Plate 2, Fig. G)
Elphidium excavatum (Terquem, 1875)

Description:
see Hayward et al. (1997)

Elphidium excavatum clavatum Cushman, 1930 (Plate 2, Fig. H)

Synonymy:
see Hayward et al. (1997)
Description:
see Hayward et al. (1997)

Remarks:
The characteristics of *E.excavatum clavatum* in the study area match the description given by Hayward et al. (1997), apart from the number of chambers generally ranging from 9 to 11, rather than from 10 to 14. Additionally, specimens are generally small, rather than small to medium.

This species is distinguished from other subspecies by the intermediate length of the septal bridges, its umbilical collar and small umbonal boss (Hayward et al., 1997). Although similar in appearance to *E.advenum maorium*, the species is distinguished from it by having wider sutural pits, more papillae, a narrower umbilical collar, lack of a keel (although in *E.advenum maorium* it is only weak), and by being less dorso-ventrally compressed.

Elphidium excavatum excavatum (Terquem, 1875) (Plate 2, Fig. I)

Synonymy:

see Hayward et al. (1997)

Description:

see Hayward et al. (1997)

Remarks:

E.excavatum excavatum is distinguished from other subspecies by its short, irregular septal bridges and depressed star-shaped umbilicus lined with papillae (Hayward et al., 1997). In the study area, the species varies in form, with two main variants, as well as numerous intermediate stages. The first variant is larger, covered in less papillae, has more inflated chambers, wider and more regular septal bridges, and has a brown coloured, glassy test which is coarsely perforate. The second variant is smaller, has a white, finely perforate test, featuring narrower and more irregular septal bridges, less inflated chambers, and more papillae. These two variants of *E.excavatum excavatum* can be regarded as end-members within the range of form within the subspecies. Therefore, no attempt was made to divide the species into the two variants. As all forms have the same environmental distribution within the estuary, it appears that the variation is not environmentally controlled, possibly reflecting different growth stages of the species.

Elphidium excavatum williamsoni Haynes, 1973 (Plate 2, Fig. J)

Synonymy:

see Hayward et al. (1997)

Description:

see Hayward et al. (1997)

Remarks:

E.excavatum williamsoni differs from other subspecies by its numerous chambers and septal bridges and lack of an umbonal boss (Hayward et al., 1997).

Elphidium hawkesburiense (Albani, 1974) (Plate 2, Fig. K)
Elphidium lene Cushman & McCulloch, 1940 (Plate 2, Fig. L)
Elphidium macellum (Fichtel & Moll, 1798) (Plate 2, Fig. M)
Elphidium silvestrii Hayward, 1997

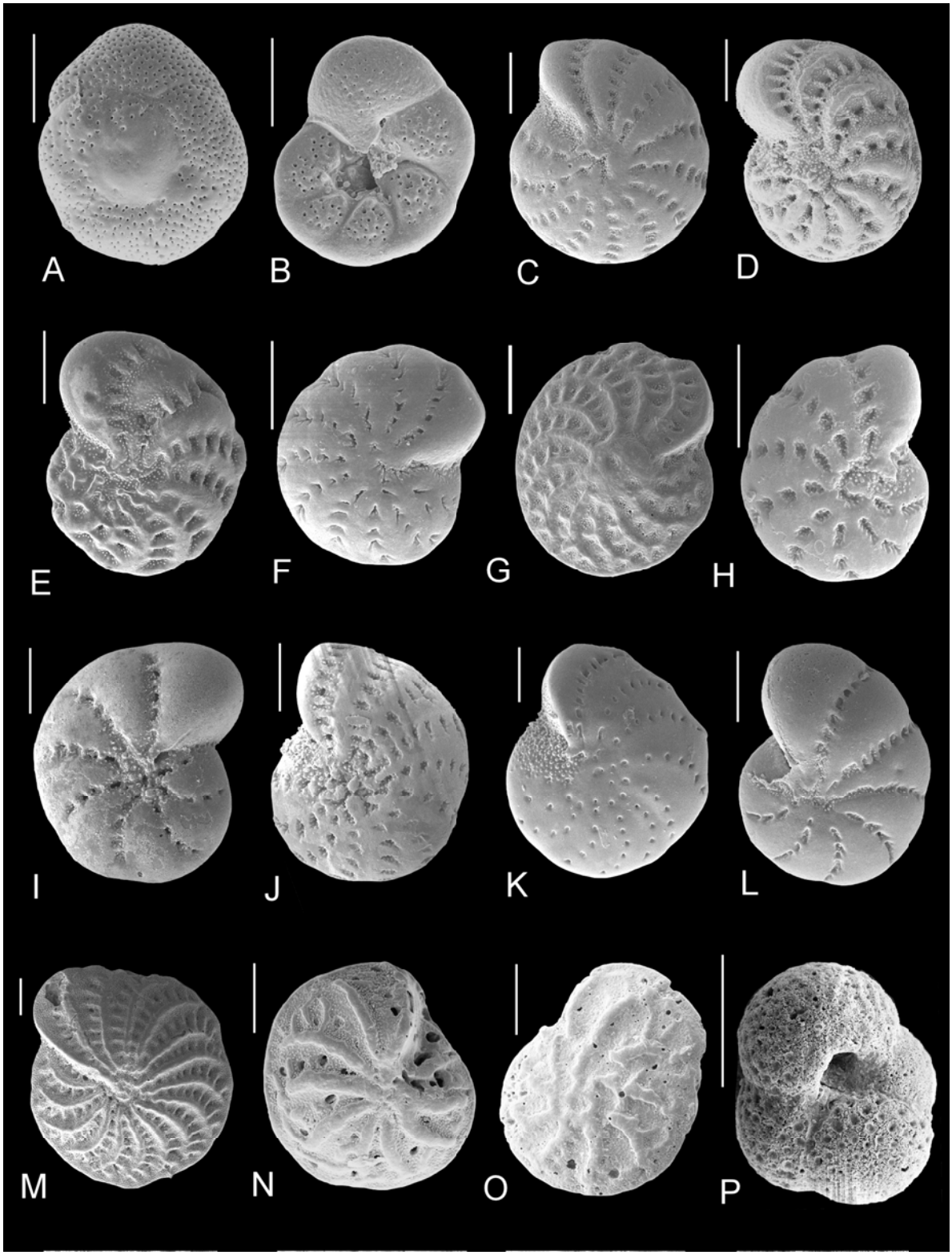

Plate 2: (All scale bars = 100 um) - **A**-**B**, *Rosalina* sp; **C**, *Elphidium advenum advenum*; **D**, *Elphidium advenum botaniense*; **E**, *Elphidium advenum limbatum*; **F**, *Elphidium advenum maorium*; **G**, *Elphidium crispum crispum*; **H**, *Elphidium excavatum clavatum*; **I**, *Elphidium excavatum excavatum*; **J**, *Elphidium excavatum williamsoni*; **K**, *Elphidium hawkesburiense*; **L**, *Elphidium lene*; **M**, *Elphidium macellum*; **N**-**O**, *Notorotalia clathrata*; **P**, *Globigerina bulloides*.

Genus *Notorotalia* Finlay, 1939

Notorotalia clathrata (Brady, 1881) (Plate 2, Fig. N-O)

Genus *Parrellina* Thalmann, 1951

Parrellina verriculata (Brady, 1881)

Family GLOBIGERINIDAE Carpenter, Parker & Jones, 1862

Genus *Globigerina* d'Orbigny, 1826

Globigerina bulloides d'Orbigny, 1826 (Plate 2, Fig. P)

Genus *Neogloboquadrina* Bandy, Frerichs & Vincent, 1967

Neogloboquadrina dutertrei (d'Orbigny, 1839)

Family GLABRATELLIDAE Loeblich & Tappan, 1964

Genus *Glabratella* Dorreen, 1948

Glabratella australensis (Heron-Allen & Earland, 1932)

Family NONIONIDAE Schultze, 1854

Genus *Nonionella* Cushman, 1926

Nonionella auris (d'Orbigny, 1839) (Plate 3, Fig. A)

Genus *Haynesina* Banner & Culver, 1978

Haynesina depressula depressula (Walker & Jacob, 1798) (Plate 3, Fig. B)

Family PARRELLOIDIDAE Hofker, 1956

Genus *Cibicidoides* Thalmann, 1939

Cibicidoides collinsi Yassini & Jones, 1995 (Plate 3, Figs. C-D)

Family PLACENTULINIDAE Kasimova & Poroshina, 1980

Genus *Patellinella* Cushman, 1928

Patellinella inconspicua (Brady, 1884) (Plate 3, Fig. E)

Family ROTALIIDAE Ehrenberg, 1839

Genus *Ammonia* Brunnich, 1772

Ammonia aoteana (Finlay, 1940) (Plate 3, Figs. F-G)

Synonymy:

Ammonia aoteana Strotz, 2003, p. 176, pl. 3, Figs. 5-8; Albani et al., 2001 (in CD-ROM).

Ammonia aoteanus Collins, 1974, p. 40, pl. 3, Figs 30a-c; Apthorpe, 1980, p. 225, pl. 27, Figs 5-6; pl. 29, Figs. 1-2; Bell, 1996, p.6.

Ammonia beccarii Cifelli, 1962, p. 119, pl. 21 & pl. 22, Figs. 1-6; Albani, 1968, p. 110, pl. 9, Figs. 7, 9, 10; Hayward, 1993, Figs. 3J-L; Hayward & Hollis, 1994, p. 213, pl. 4, Figs. 1-3; Hollis et al., 1995, Figs. 3k,l; Hayward et al., 1996, pl. 2, Figs. 8,9.

Ammonia beccarii f. *aoteana* Hayward and Hollis, 1994, p. 213, pl. 4, Figs. 1-3.

Ammonia parkinsoniana f. *aoteana* Hayward et al., 1999, p. 162, pl. 16, Figs. 7-9.

Rotalia beccarii Cushman, 1928, p. 104, pl. 15, Figs. 3-7.

Streblus aoteanus Finlay, 1940, p. 46.

Description:

See Albani et al., 2001

Remarks:

The identification of species, subspecies and formae of *Ammonia* has been problematic, and is discussed extensively in Bell (1996). Historically, specimens of the genus *Ammonia* identified in New South Wales have been referred to as *Ammonia beccarii* (Linne), whereas, those identified in Victoria have been referred to as *Ammonia aoteana* (Finlay). Apthorpe (1980) proposed that *Ammonia aoteana* is a cool temperate morphotype of *Ammonia beccarii*. Hayward et al. (1997) describe *Ammonia beccarii* as being absent in New Zealand, where it is instead represented by *Ammonia parkinsoniana*, which occurs in two formae: *aoteana* and *tepida*. Albani et al. (2001) proposed that *Ammonia parkinsoniana* f. *aoteana* is actually *Ammona aoteana* in Australia. Such would place the geographical distribution of *A.aoteana* as including Victoria and New Zealand, but not New South Wales. Therefore, although the distinction between *aoteana* and *beccarii* remains uncertain, specimens of *Ammonia* in the current study are assigned to *aoteana* mainly based upon the geographical (cool temperate) location of the study area.

Ammonia pustulosa *(*Albani & Barbero 1982) (Plate 3, Figs. H-I)

Family TRICHOHYALIDAE Saidova, 1981

Genus *Aubignyna* Margerel, 1970

Aubignyna perlucida (Heron-Allen & Earland, 1913) (Plate 3, Figs. J-K)

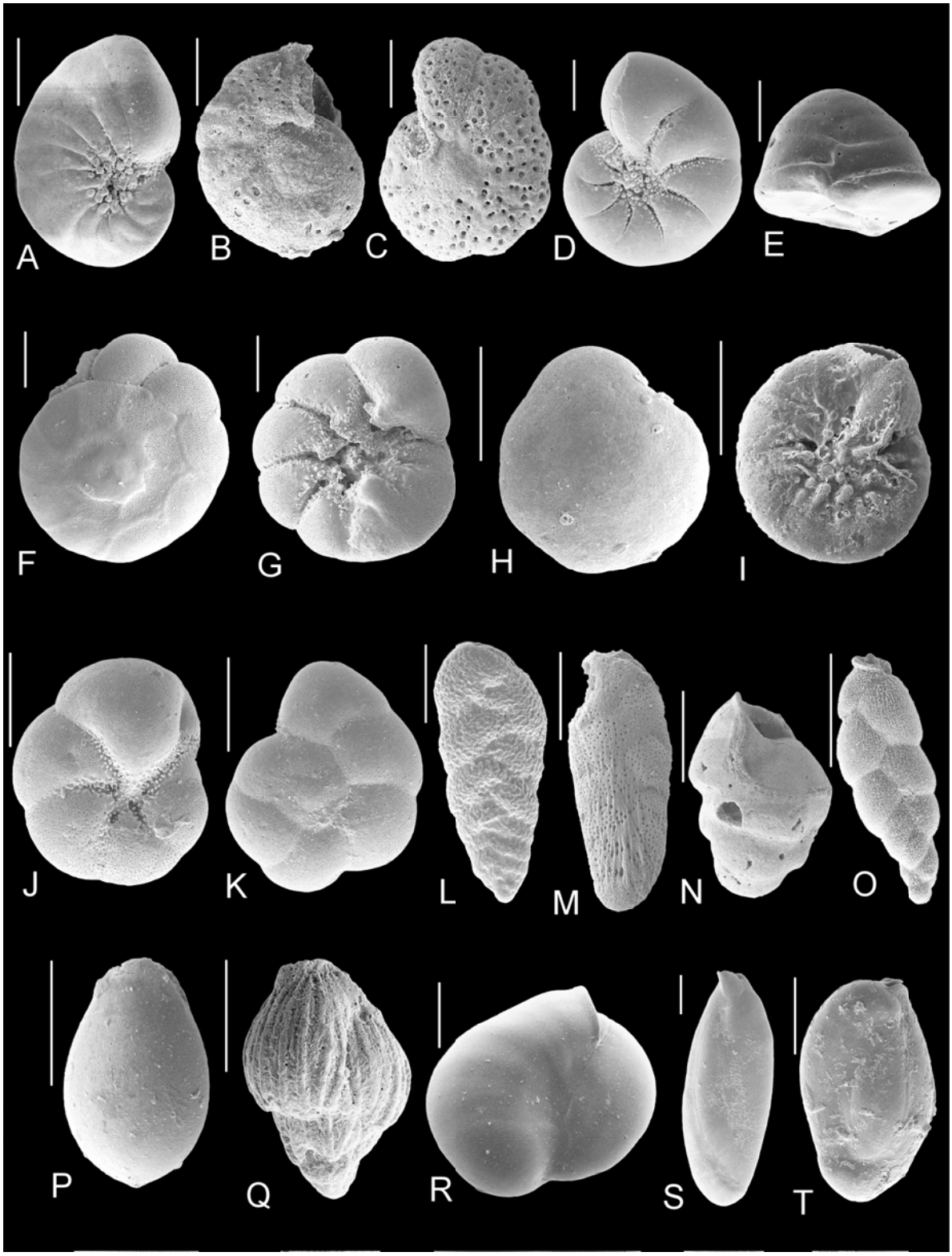

Plate 3: (All scale bars = 100 um) - **A**, *Nonionella auris*; **B**, *Haynesina depressula depressula*; **C-D**, *Cibicidoides collinsi*; **E**, *Patellinella inconspicua*; **F-G**, *Ammonia aoteana*; **H-I**, *Ammonia pustulosa*; **J-K**, *Aubignyna perlucida*; **L**, *Bolivina doniezi*; **M**, *Brizalina striatula*; **N**, *Bulimina gibba*; **O**, *Spiroloxostoma croarae*; **P**, *Fissurina globoscaudata*; **Q**, *Guttulina regina*; **R**, *Miliolinella circularis*; **S**, *Quinqueloculina oblonga*; **T**, *Quinqueloculina seminula*.

Genus *Brizalina* Costa, 1856

Superfamily Buliminacea Jones, 1875
Family BOLIVINIDAE Glaessner, 1937
Genus *Bolivina* d'Orbigny, 1839
Bolivina doniezi Cushman & Wickenden, 1928 (Plate 3, Fig. L)
Bolivina pseudoplicata Heron-Allen & Earland, 1930
Brizalina striatula (Cushman, 1922) (Plate 3, Fig. M)

Family BULIMINIDAE Jones, 1875
Genus *Bulimina* d'Orbigny, 1826
Bulimina elongata Cushman & Parker, 1937
Bulimina gibba Fornasini, 1902 (Plate 3, Fig. N)
Bulimina marginata d'Orbigny, 1826

Family FURSEKOINIDAE Loeblich & Tappan, 1961
Genus *Fursenkoina* Loeblich & Tappan, 1961
Fursenkoina complanata (Egger, 1893)

Family SIPHOGENERINOIDIDAE Saidova, 1981
Genus *Siphogenerina* Schlumberger, 1883
Siphogenerina raphana (Parker & Jones, 1865)

Genus *Spiroloxostoma* Conata, 1964
Spiroloxostoma croarae (Conato, 1964) (Plate 3, Fig. O)

Family UVIGERINIDAE Haeckel, 1894
Genus *Uvigerina* d'Orbigny, 1826
Uvigerina bassensis Parr, 1950

Suborder LAGENINA Delage & Herouard, 1896
Superfamily Nodosariacea Ehrenberg, 1838
Family ELLIPSOLAGENIDAE Silvestri, 1923
Genus *Favulina* Patterson & Richardson, 1987
Favulina hexagona (Williamson, 1848)

Genus *Heteromorphina* Jones, 1984

Heteromorphina heteromorpha Parr, 1950

Genus *Fissurina* Reuss, 1850

Fissurina fasciata carinata (Sidebottom, 1906)

Fissurina globosocaudata Albani & Yassini, 1989 (Plate 3, Fig. P)

Genus *Oolina* d'Orbigny, 1839

Oolina ovoidea Yassini & Jones, 1995

Family LAGENIDAE Reuss, 1863

Genus *Lagena* Walker & Jacob, 1798

Lagena doveyensis Haynes, 1973

Lagena spiratiformis McCulloch, 1981

Lagena sulcata peculiaris Cushmann & McCulloch, 1950

Family POLYMORPHINIDAE d'Orbigny, 1839

Genus *Guttulina* d'Orbigny, 1839

Guttulina austriaca d'Orbigny, 1846

Guttulina pacifica (Cushman & Ozawa, 1928)

Guttulina regina (Brady, Jones & Parker, 1871) (Plate 3, Fig. Q)

Family VAGINULINIDAE Reuss, 1860

Subfamily LENTICULININAE Chapman, Parr & Collins, 1934

Genus *Lenticulina* Lamarck, 1804

Lenticulina limbosa (Reuss, 1863)

Genus *Vaginulina* d'Orbigny, 1826

Vaginulina cf. ***advena pauciloculata*** Cushman & Grey, 1946

Suborder Miliolinina Delage & Herouard, 1896

Superfamily Miliolacea Ehrenberg, 1839

Family HAUERINIDAE Schwager, 1876

Genus *Miliolinella* Wiesner, 1931

Miliolinella circularis (Bornemann, 1855) (Plate 3, Fig. R)

Miliolinella lakemacquariensis Yassini & Jones, 1995

Miliolinella pyrgoformis Yassini & Jones, 1995

Genus *Quinqueloculina* d'Orbigny, 1826

Quinqueloculina lamarckiana d'Orbigny, 1839

Quinqueloculina oblonga (Montagu, 1803) (Plate 3, Fig. S)

Quinqueloculina poeyana d'Orbigny, 1839

Quinqueloculina seminula (Linne, 1767) (Plate 3, Fig. T)

Quinqueloculina subpolygona Parr, 1946

Suborder Spirillinina Hohenegger & Piller, 1975

Family SPIRILLINIDAE Reuss & Fritsch, 1861

Genus *Spirillina* Ehrenberg, 1843

Spirillina vivipara Ehrenberg, 1843

PHYLUM ARTHROPODA

Subphylum CRUSTACEA Pennant, 1777

Class OSTRACODA Latreille, 1806

Order PODOCOPIDA Mueller, 1894

Suborder PLATYCOPINA Sars, 1866

Family CYTHERELLIDAE Sars, 1866

Genus *Cytherella* Jones, 1845

Cytherella sp. aff ***lata*** Brady, 1880 (Plate 4, Fig. A)

Suborder PODOCOPINA Sars, 1866

Family AUSTRALOCYTHERIDAE Hartmann, 1980

Genus Australocytheridea McKenzie, 1967

Australocytheridea vandenboldi McKenzie, 1967 (Plate 4, Fig. B-C)

Family BAIRDIIDAE Sars, 1888

Genus *Paranesidea* Maddocks, 1969

Paranesidea sinusaquilensis (Hartmann, 1979) (Plate 4, Figs. D-F)

Synonymy:

Bairdoppilata sinusquilensis Hartmann, 1979, p. 220, pl. 1, Figs. 8-18; Hartmann, 1980, p. 113, pl. 2, Figs. 1-3; Yassini and Jones, 1987, p. 818, Fig. 1.8-1.10.

Paranesidea sinusaquilensis Yassini and Jones, 1995, p. 305, Figs. 46, 48-49, 57, 59; Neil, 2000, Fig 2h.

Description:

See Yassini and Jones, 1995.

Remarks:

There is some variation of form within this species, with the dorsal margin of some specimens being more angular and less rounded.

Family BYTHOCYTHERIDAE Sars, 1929

Subfamily PSEUDOCYTHERINAE Schneider, 1960

Genus *Microceratina* Swanson, 1980

Microceratina quadrata Swanson, 1980 (Plate 4, Figs. G-I)

Synonymy:

Microceratina quadrata Swanson, 1980, p. 205, Figs. 6-8, 15-16, 27-28; Yassini and Jones, 1995, p. 318, Figs. 135-137, 139.

Description:

See Swanson, 1980

Remarks:

Only five specimens of this species were found in the study area. Specimens of the species differed slightly to those illustrated in Yassini and Jones (1995), by the postero-ventral lobe being less pronounced, as in New Zealand specimens of Swanson (1980).

Family CYTHERIIDAE Baird, 1850

Subfamily CYTHERINAE Baird, 1850

Genus *Microcytherur*a Mueller, 1894

Microcytherura australis McKenzie, 1967 (Plate 4, Figs. J-N)

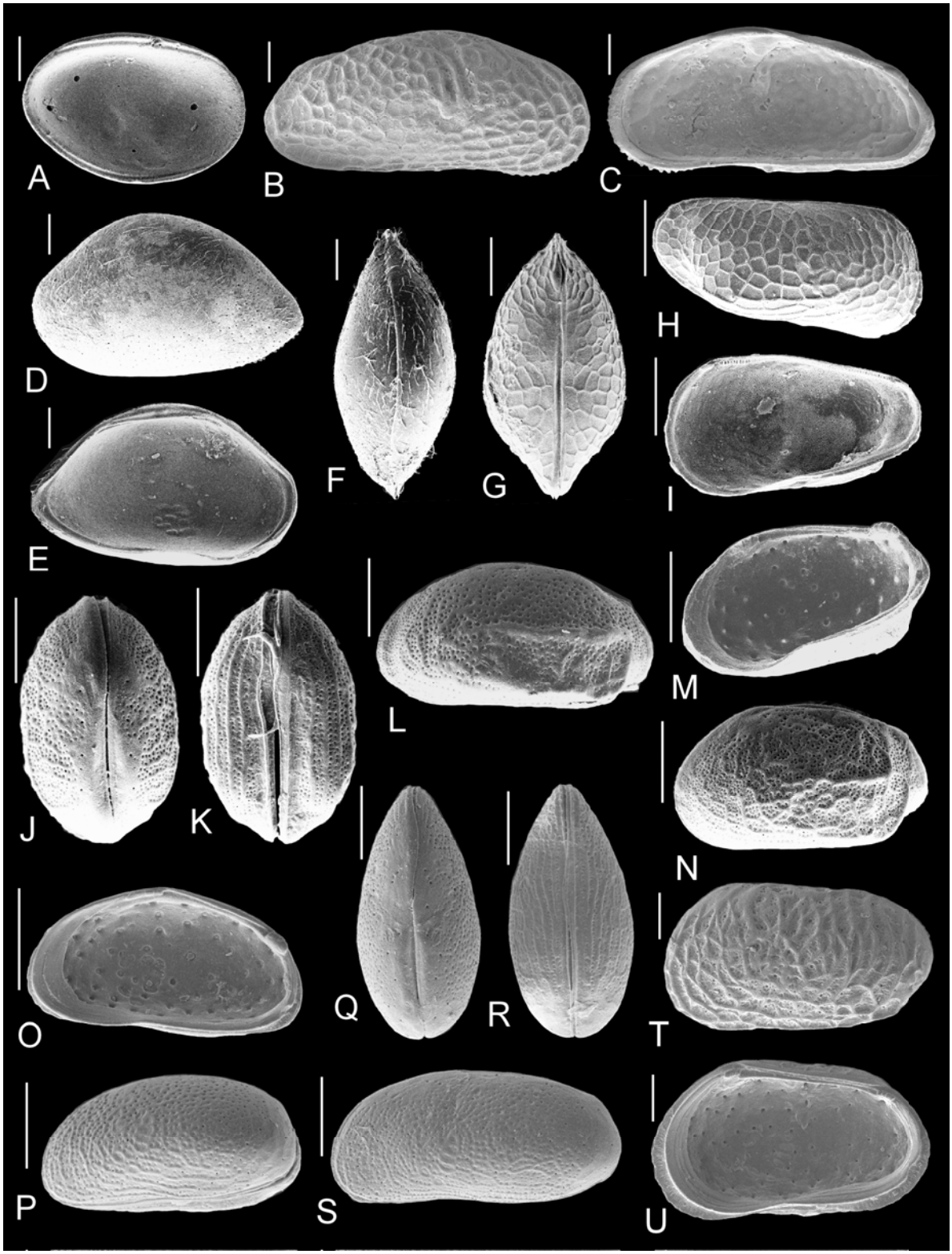

Plate 4: (All scale bars = 100 um) - **A**, *Cytherella* sp. aff *lata*; **B-C**, *Australocytheridea vandenboldi*; **D-F**, *Paranesidea sinusaquilensis*; **G-I**, *Microceratina quadrata*; **J-N**, *Microcytherura australis* (L=male; J-K, M-N=female); **O-S**, *Microcytherura triebeli* (S=female; O-R=male); **T-U**, *Microcytherura (Loxocythere) hornibrooki*.

Synonymy:

Microcytherura australis McKenzie, 1967, p. 79, pl. 11, Fig. 11; Yassini and Jones, 1995, p. 346, Figs. 597, 599, 602-604.

Description:

See McKenzie, 1967.

Remarks:

Variation of form within the species in the study area can be atrributed to sexual dimporhism, as previously observed by McKenzie (1967) and Yassini and Jones (1995), with males (Fig. L) being more elongate and narrower than females (Figs. J-K, M-N).

Microcytherura triebeli McKenzie, 1967 (Plate 4, Figs. O-S)

Synonymy:

Microcytherura triebeli McKenzie, 1967, p. 80, Fig. 2i; Yassini and Jones, 1995, p. 348, Figs. 596, 598, 600-601.

Description:

See McKenzie, 1967.

Remarks:

Variation of form within the species in the study area can be attributed to sexual dimorphism, as previously observed by McKenzie (1967) and Yassini and Jones (1995). There is some confusion as to which sex is larger than the other, as Yassini and Jones (1995) describe females to be shorter than males, whereas, McKenzie (1967) describes males to be smaller than females. However, measurements of specimens belonging to both sexes in McKenzie (1967) indicate females to be more elongate than males. In plate 4, Figures O-R display male specimens, and Figure S displays a female specimen.

Subgenus *Loxocythere* Hornibrook, 1952

Microcytherura (Loxocythere) hornibrooki (McKenzie, 1967) (Plate 4, Figs. T-U)

Subfamily CYTHEREIDEINAE Sars, 1925

Genus *Perissocytheridea* Stephenson, 1938

Perissocytheridea conistonbayensis Yassini & Jones, 1995 (Plate 5, Figs. A-C)

Subfamily CYTHERETTINAE Triebel, 1952

Genus *Cytheretta* Mueller, 1894

Cytheretta robusta Yassini & Jones, 1995 (Plate 5, Figs. D-E)

Family CYTHEROMATIDAE Elofson, 1939

Genus *Paracytheroma* Juday, 1907

Paracytheroma subaustralis (McKenzie, 1978) (Plate 5, Figs. F-I)

Synonymy:

Cytheroma subaustralis McKenzie, 1978, p. 178, Figs. 30, 35-42.

Paracytheroma subaustralis Hartmann, 1980, p. 128, Figs. 51-56; Yassini and Jones, 1987, p. 822, Fig. 5.22; Yassini and Wright, 1988, p. 167, Fig. 7c,d; Yassini and Jones, 1995, p. 313, Figs. 71-74.

Description:

See Yassini and Jones, 1995.

Remarks:

There is some variation of form within the species, mainly relating to the broadly rounded anterior margin. The position of maximum width of the anterior margin varies in position, generally being mid-carapace height, yet is more ventral in some specimens. This variation is also visible in Figures of the species in Yassini and Jones (1995).

Family CYTHERURIDAE Mueller, 1894

Genus *Semicytherura* Wagner, 1957

Semicytherura sp. (Plate 5, Fig. J)

Description:

The carapace is very small, elongate subrectangular with a straight dorsum and slightly inflexed ventrum. The anterior end is broadly rounded, and the posterior end has a short dorsal cauda. The posteroventral area is depressed. Inner lamella, and hinge and muscle scars are typical of the genus. Surface ornamentation consists of a central and ventral carina. The central carina runs from a slightly ventral position on the anterior margin along

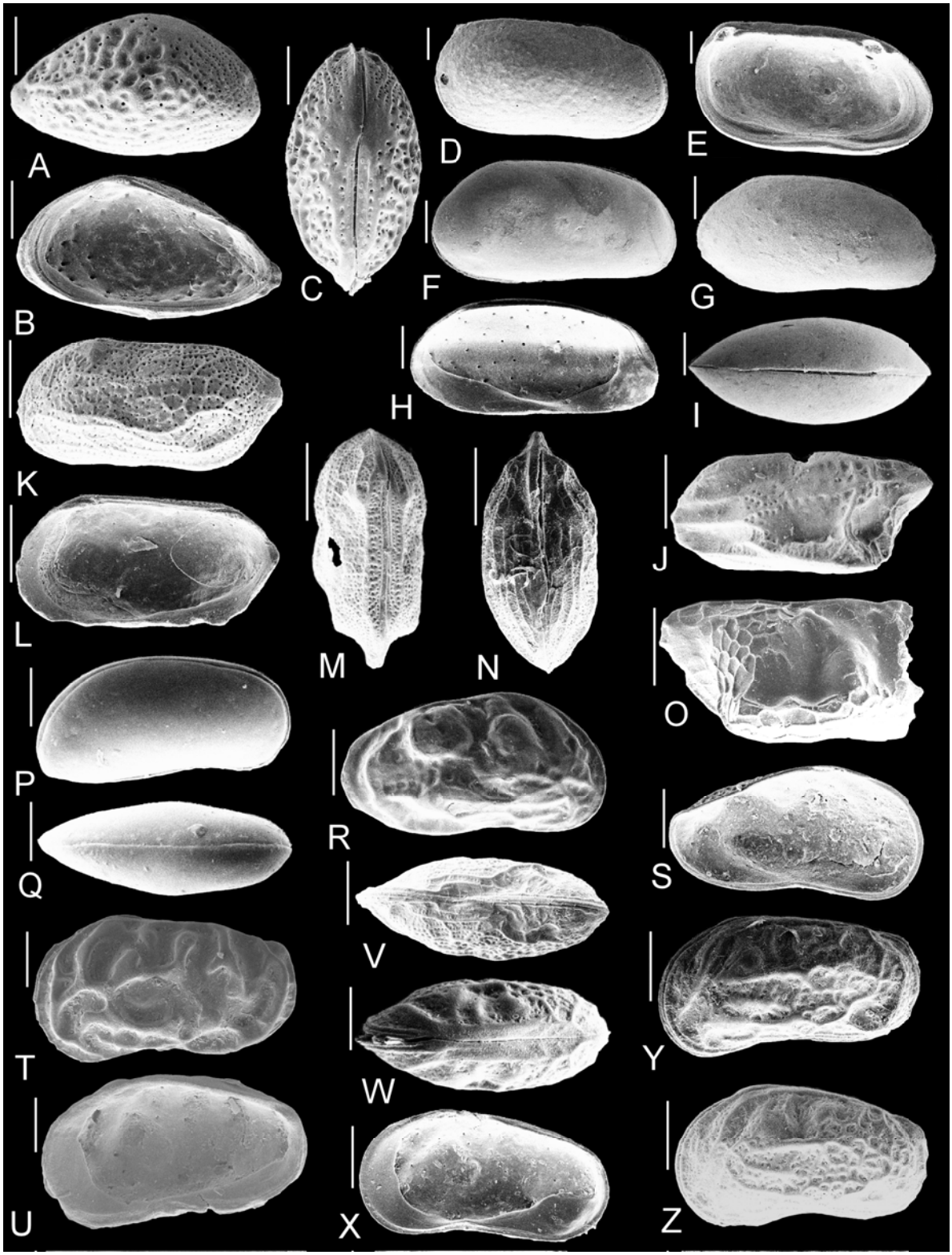

Plate 5: (All scale bars = 100 um) - **A-C**, *Perissocytheridea conistonbayensis*; **D-E**, *Cytheretta robusta*; **F-I**, *Paracytheroma subaustralis*; **J**, *Semicytherura* sp.; **K-N**, *Semicytherura taylori*; **O**, *Cytheropteron* sp.; **P-Q**, *Parakrithella australis*; **R-S**, *Callistocythere dorsotuberculata*; **T-U**, *Callistocythere puri*; **V-Z**, *Leptocythere hartmanni*.

to the short dorsal cauda on the posterior margin, bifurcating twice to the posteroventral area where it links with the ventral carina. A network of fine reticulation and micropunctation covers the central and posterior areas, appearing to be absent from the anterior. Strong reticulation occurs in the posterodorsal region.

Remarks:

The description of this species is based upon a single specimen found in sample #14, adjacent to the inlet channel. As this specimen displays some signs of erosion, it is possible it may have been transported by tidal currents into the estuary from Frederick Henry Bay.

The species is quite similar in appearance to *Semicytherura mckenziei* of Yassini and Jones (1995), yet differs from it by lacking a spinuous posteroventral region, as well as by apparently lacking a dorsal carina (although it may have been eroded away), and by having different central carina bifurcation pattern, and having generally less strong reticulation.

Semicytherura taylori (McKenzie, 1967) (Plate 5, Figs. K-N)

Genus *Cytheropteron* Sars, 1866

Cytheropteron sp. (Plate 5, Fig. O)

Description:

The carapace is small, subrhomboidal, and thin. The ventrum is winged and convex, being inflected near the anterior end. The dorsum is straight. The posterior end is oblique ventrally, and has a subdorsal cauda. The central area features two lobe-like structures which merge ventrally, protruding outward to form an ala. A hexagonal pattern of reitculation, with some faint ridges, covers the dorsal, ventral, anterior and posterior areas, being absent from the central area.

Remarks:

This species is represented by one specimen obtained in sample #60. This specimen has a broken anterior end, and shows some signs of erosion.

In appearance, the species looks quite similar to Cytheropteron sp. of Yassini and Jones (1995). However, slight differences to that species include: the central area being more depressed, apparent absence of the four distinct subparallel ridges on the ventral side of the ala, and a lack of any reticulation within central area.

Family KRITHIDAE Mandelstam, 1958

Genus *Parakrithella* Hanai, 1959

Parakrithella australis McKenzie, 1967 (Plate 5, Figs. P-Q)

Family LEPTOCYTHERIDAE Hanai, 1957

Genus *Callistocythere* Ruggieri, 1953

Callistocythere dorsotuberculata Hartmann, 1982 (Plate 5, Figs. R-S)

Callistocythere puri McKenzie, 1967 (Plate 5, Figs. T-U)

Genus *Leptocythere* Sars, 1925

Leptocythere hartmanni (McKenzie, 1967) (Plate 5, Figs. V-Z)

Synonymy:

Callistocythere hartmanni McKenzie, 1967, p. 81, pl. 12, Fig. 5.

Leptocythere hartmanni Hartmann, 1978, p. 79, pl. 4, Figs. 1-2; Hartmann, 1979, p. 226, pl. 3, Figs. 3-8; Hartmann, 1980, p. 123, Fig. 5y; Hartmann, 1981, p. 102, pl. 2, Fig. 9-14; Hartmann, 1982, p. 122, pl. 2, Figs. 1-2; Yassini and Jones, 1987, p. 820, Fig. 2.7-2.9; Yassini and Wright, 1988, p. 165, Fig. 7k,l; Yassini et al., 1993, p. 386, pl. 3, Fig. 45; Yassini and Jones, 1995, p. 331, Figs. 223, 225, 228.

Description:

See Yassini and Jones, 1995.

Remarks:

There is some variability in the degree of surface reticulation of the carapace in *L.hartmanni* within the study area, with some forms being generally smoother and featuring less obvious secondary ornamentation. Some of this variation in form may be attributed to surface erosion of specimens within the intertidal zone (where the species is most common).

Subfamily CAUDOLEPTOCYTHERINAE (Yassini & Jones, 1995)

Genus *Caudoleptocythere* (Yassini & Jones, 1995)

Caudoleptocythere vellicata (Brady, 1880) (Plate 6, Figs. A-C)

Family LOXOCONCHIDAE Sars, 1925

Genus *Loxoconcha* Sars, 1866

Loxoconcha australis Brady, 1880 (Plate 6, Figs. D-F)

Synonymy:

Loxoconcha australis Brady, 1880, p. 119, pl. 28, Fig. 5a-f; McKenzie, 1967, p. 86, pl. 12, Figs. 10-11; Yassini and Jones, 1987, p. 825, Fig. 3.20-3.22; Yassini and Kendrick, 1999, Fig. 4h-l; Yassini and Jones, 1995, p. 340, Figs. 310-314.

Description:

See Yasinni and Jones, 1995.

Remarks:

Yassini and Jones (1995) describe the species as displaying pronounced sexual dimorphism, and in their Figures of the species indicate males to be more elongate and more rectangular. In plate 6, Figure F displays a male specimen, and Figures D-E female specimens.

Loxoconcha cumulus (Brady, 1880) (Plate 6, Fig. G)

Loxoconha gilli McKenzie, 1967 (Plate 6, Fig. H)

Genus *Cytheromorpha* Hirschmann, 1909

Cytheromorpha robusta Yassini & Jones, 1995 (Plate 6, Fig. I-K)

Family MICROCYTHERIDAE Klie, 1938

Subfamily MICROCYTHERINAE Klie, 1938

Genus *Microcythere* Mueller, 1894

Microcythere macphersoni McKenzie, 1967 (Plate 6, Figs. L-N)

Family OSTICYTHERIDAE Hartmann, 1980

Genus *Osticythere* Hartmann, 1980

Osticythere baragwanathi (Chapman, Crespin & Keble, 1928) (Plate 6, Figs. O-Q)

Family PARACYPRIDIDAE Sars, 1923

Genus *Tasmanocypris* McKenzie, 1979

Tasmanocypris dietmarkeyseri? (Hartmann, 1979) (Plate 6, Figs. R-S)

Synomyny:

Aglaiella dietmarkeyseri Hartmann, 1979, p. 269, pl. 13, Figs. 8-9; Yassini and Jones, 1987, p. 831, Fig. 5.24; Yassini and Jones, 1995, 309, Figs. 103, 106; Neil, 2000, Fig. 2b.

Description:

See Yassini and Jones, 1985.

Remarks:

There was some uncertainty in the identification of this species, due to the tendency of specimens to curl as a consequence of the thin carapace. There are some differences between specimens of the species in the current study and those illustrated in Hartmann (1979) and Yassini and Jones (1987), mainly in relation to the shape of the dorsal outline; however, the species, as illustrated in Neil (2000), is a very close match. Consequently, the name of the species in this study is followed by a question mark, indicating that its identification has a degree of doubt.

Genus *Phlyctenophora* Brady, 1880

Phyctenophora zealandica Brady, 1880 (Plate 6, Fig. T-U)

Family PARADOXOSTOMIDAE Brady & Norman, 1889

Genus *Paradoxostoma* Fischer, 1855

Paradoxostoma sp. (Plate 6, Fig. V)

Description:

Carapace elongate, subfusiform-ovate, medium size, and laterally compressed.. The dorsum is curved to slightly angular, ventrum convex posteriorly with slight inflexion mid-length. Anterior end obtuse and evenly rounded. Posterior end terminates in distinct subdorsal caudal process. On posterior end, ventral side of cauda is acuminate, whereas, dorsal side of cauda is straight, with slight inflexion. Surface smooth.

Remarks:

Compared to other species of *Paradoxostoma*, the species is most similar to *Paradoxostoma albaniense* (Hartmann) and *Paradosostoma crustaecolum* (Hartmann). However, it differs from *P.albaniense* mainly by the carapace being broader, less ovate, and the dorsum being more angular. Differences also occur in the posterior area, by the

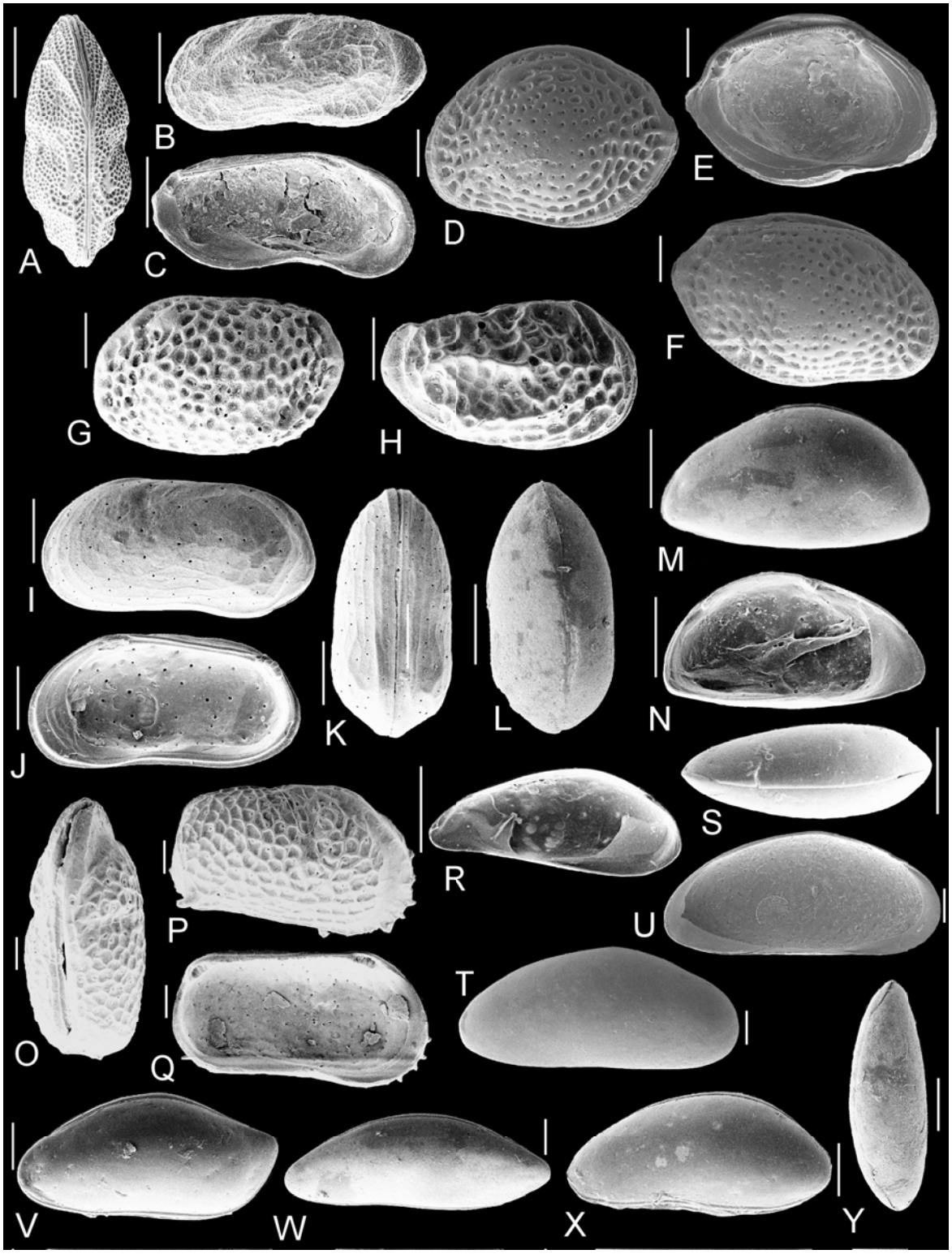

Plate 6: (All scale bars = 100 um) - **A-C**, *Caudoleptocythere vellicata*; **D-F**, *Loxoconcha australis* (D-E=female; F=male); **G**, *Loxoconcha cumulus*; **H**, *Loxoconha gilli*; **I-K**, *Cytheromorpha robusta*; **L-N**, *Microcythere macphersoni*; **O-Q**, *Osticythere baragwanathi*; **R-S**, *Tasmanocypris dietmarkeyseri*?; **T-U**, *Phyctenophora zealandica*; **V**, *Paradoxostoma* sp.; **W**, *Paradoxostoma promunturiumphysicicolum*; **X-Y**, *Paracytherois portphillipensis*.

dorsal side of the cauda being straighter and slightly convex, and by the ventral side being more obtuse, and the cauda being more dorsal in position. Differences with *P.crustaecolum* include greater elongation of the carapace, and greater angularity of the dorsum.

Only one specimen of this species was found, in outermost sample #4, suggesting that it prefers marine conditions.

Paradoxostoma promunturiumphysicicolum Hartmann, 1979 (Plate 6, Fig. W)

Genus *Paracytherois* Muller, 1894
Paracytherois portphillipensis McKenzie, 1967 (Plate 6, Figs. X-Y)

Genus *Sclerochilus* Sars, 1866
Sclerochilus australiensis Hartmann, 1979 (Plate 7, Figs. A-C)

Family PECTOCYTHERIDAE Hanai, 1957
Genus *Mckenzieartina* Bentley, 1988
Mckenzieartina portjacksonensis (McKenzie, 1967) (Plate 7, Figs. D-F)

Family TRACHYLEBERIDIDAE Sylvester-Bradyley, 1948
Subfamily TRACHYLEBERIDINAE Sylvester-Bradyley, 1948
Genus *Trachyleberis* Brady, 1898
Trachyleberis (?) sp. (Plate 7, Figs. G-I)

Description:

Carapace subquadrate, large, strongly calcified. Dorsum straight, ventrum slightly sinuous anteroventrally. Anterior end broadly rounded with 16-17 marginal denticulations. Posterior end oblique dorsally and ventrally, forming a very broad subventral cauda. Posteroventral margin is covered in 6-8 marginal denticulations. Inner lamella relatively narrow. Hinge in right valve consists of two elongate and crenulate anterior and posterior elements (teeth) and a finely denticulate median groove and weakly crenulated median bar. Central muscle scar is depressed and forms a deep concavity, which is expressed by a distinct sub central tubercule on the external surface. Surface of carapace covered in a loose, complex pattern of moderately strong reticulation. Small nodes, with a central hole on top, are scattered across surface, yet occur at junctions within the reticulation pattern.

Remarks:

The species is tentatively assigned to *Trachyleberis* due to it possessing many characteristics typical of the genus, including shape (subrectangular with nearly straight dorsal and ventral margins), ornamentation (spines, tubercles, pores running out through tubercles, marginal denticulation), as well as the depressed central muscle scar on internal surface expressed as a subcentral tubercle on exterior surface. However, the presence of a different hinge structure to that typical of the *Trachyleberis* attaches some doubt in placing the species within the genus.

Within *Trachyleberis*, the species closely resembles *Trachyleberis jervisbayensis* in external outline and internal view and also features a similar pattern of reticulation and marginal denticulation, yet, it is significantly different in side view and has different hinge structure. The species also resembles *Trachyleberis militaris* in external outline and internal view and marginal reticulation, yet has very different surface reticulation.

It is also worth noting that *Trachyleberis* sp. has significant similarities with *Cythere wyville thomsoni* (Brady) which was discovered by Brady on the H.M.S. Challenger voyage of 1873-1876. *C.wyville thomsoni* has same the shape (in external and side view), reticulation pattern, broad subcentral tubercle, and marginal denticulation, yet appears to lack spines/tubercules over the external surface. The spines along the posterior margin of *Cythere wyville thomsoni* (Brady) are also significantly longer than those of *Trachyleberis* sp.

Trachyleberis ("Ponticocythereis") jervisbayensis Yassini & Jones, 1995 (Plate 7, Figs. J-L)

Trachyleberis (Ponticocytheresis) militaris (Brady, 1866) (Plate 7, Figs. M-Q)

Synomyny:

Cythereis militaris Brady, 1866, p. 385, pl. 61, Fig. 9a-d

Ponticocythereis miltaris McKenzie, 1967, p. 97, pl. 13, Fig. 4.

Actinocythereis lainensis Wouters, 1981, p. 6, pl. 3, Fig. 2a-f.

Actinocythereis militaris Hartmann, 1980, p. 130, pl. 8, Figs. 7-11.

Actinocythereis (Ponticocythereis) militaris Yassini and Wright, 1988, p. 167, Fig. 5o-p.

Trachyleberis (Ponticocytheresis) militaris Yassini and Jones, 1995, p. 353, Figs. 408-411.

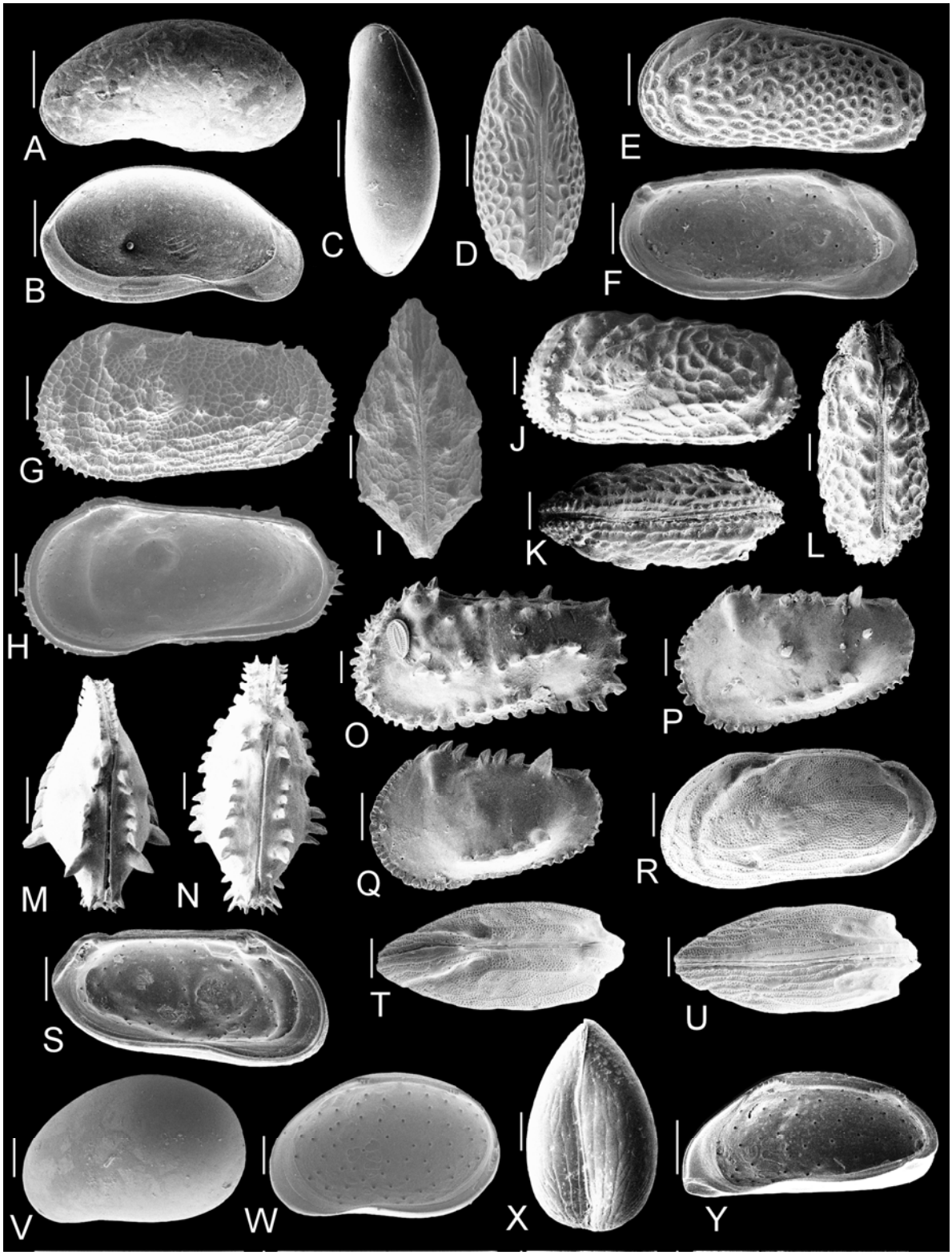

Plate 7: (All scale bars = 100 um) - **A-C**, *Sclerochilus australiensis;* **D-F**, *Mckenzieartina portjacksonensis*; **G-I**, *Trachyleberis* (?) sp.; **J-L**, *Trachyleberis ("Ponticocythereis") jervisbayensis*; **M-Q**, *Trachyleberis (Ponticocytheresis) militaris* (M, P-Q=juveniles; N-O=adults); **R-U**, *Australimoosella* spec.133; **V-W**, *Xestoleberis cedunaensis*, **X-Y**, *Xestoleberis chilensis austrocontinentalis*.

Description:

See Yassini and Jones, 1995.

Remarks:

In the study site, significant variation of form was observed and is considered to be a result of the different growth stages of the species. Figures M-Q (in Plate 7) show how juveniles of the species are smoother, have finer denticulation/spines, and lack the central lines of spines. One specimen (Fig. P) appears to be at a growth stage inbetween that of adult and juvenile, and has a weakly developed central line of spines. Further confirmation that these different forms belong to the same species, is gained by the environmental distribution of the juveniles being identical to that of the adults.

Juveniles of *T.militaris* were similarly identified by Hartmann (1980); however, some authors (Bell et al., 1995; Neil, 2000) have continued to identify them as a species of *Pterygocythereis*.

Subfamily PHACORHABDOTINAE Grundel, 1969

Genus *Australimoosella* Hartmann, 1978

Australimoosella spec.133 Hartmann, 1980 (Plate 7, Figs. R-U)

Synomyny:

Australimoosella spec.133 Hartmann, 1980, p. 133, pl. 9, Figs. 5 – 7.

Description:

See Hartmann, 1980.

Remarks:

Hartmann (1980) gave this species open nomenclature.

Family XESTOLEBERIDIDAE Sars, 1928

Genus *Xestoleberis* Sars, 1866

Xestoleberis cedunaensis Hartmann, 1980 (Plate 7, Figs. V-W)

Xestoleberis chilensis austrocontinentalis Hartmann, 1978 (Plate 7, Figs. X-Y)